THE SPECIALISTS' SERIES.

ON THE CONVERSION OF HEAT INTO WORK.

ANDERSON.

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OF

HEAT INTO WORK.

A Practical Handbook on Heat-Engines.

BY

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PREFACE.

THE Council of the Society of Arts and Manufactures invited the Author of this work to deliver a course of lectures upon the conversion of heat into useful work; and in accordance with this resolution the course, which formed the foundation for the present work, was delivered in the Session of 1884–85. The object of the lectures was to popularise the doctrine that, in heat-engines, the work given out is due to the conversion of the molecular motion of heat into the visible motion which it was desired to produce; and further to illustrate, by numerous practical examples, the applicability of the doctrine of Sadi Carnot to defining the limits within which improvement in the economical working of heat-engines was possible.

In the hope of making the modern views with respect to the action of heat more real and practical, the Author adopted the method of working out his investigations by means of numerical examples, and comparing the results with those obtained in actual practice.

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ON THE CONVERSION OF HEAT INTO WORK.

CHAPTER I.

THE present century is distinguished by the rapidity with which the application of heat to the service of man has been extended. Most of the inventors of heat-engines and furnaces have, however, been ignorant of the principles upon which the action of their inventions depended; and lamentable errors, accompanied by waste of time and money, have been the consequence.

It is only within the last hundred years that the true nature of heat has been gradually explained. The experiments of Count Rumford and Sir Humphry Davy proved that heat was not a material substance, because it was capable of being developed to an unlimited extent by the application of external work, without any alteration in the weight or chemical composition of the substance from which the heat appeared to emanate. This was a great step in advance, and it was followed by one of equal importance, when Joule, Colding, Mayer, and others demonstrated experimentally that a given quantity of heat was always equivalent to a corresponding amount of work, and the

almost necessary deduction which followed, namely, that heat was a consequence of the transformation of the coarse, visible motion of mechanical work into the invisible motion of the molecules of a body or the undulations of the mysterious medium, pervading all nature, through which are propagated the rays of light and radiant heat.

Gradually, likewise, it came to be perceived that there was a relationship between heat and certain other phenomena, such as light, electricity, and chemical action, and we have at last been able to establish, by the irrefragable evidence of experiment, that these manifestations are forms of energy convertible, for the most part, into each other, and all having a mechanical equivalent.

Before discussing the principles of action of various forms of heat-engines, it will be convenient to consider, briefly, some of the physical laws to which frequent reference will be made, because by so doing the necessity of seeking for information in other works will be avoided.

We are indebted to Sir Isaac Newton for the first clear exposition of the laws of motion, and so complete was the conception which that great man had of these laws, that his definitions, formulated 200 years ago, cannot be improved even at this day, and some of the consequences hidden in them have only been discerned, or at any rate appreciated, in quite modern times.

According to the first law of motion, "every body continues in a state of rest or of uniform motion in a straight line, except in so far as it may be compelled by impressed forces to change that state." The first portion of this law —namely, that a body will remain at rest so long as something does not make it move will be readily granted; but the second portion is not so obvious, because we have no experience of it on the earth. We know by observation

that anything set in motion and left to itself will, sooner or later, come to rest; but we also know that by reducing friction and the resistance of the air, motion may be greatly prolonged. A boy, starting with the same impetus, will slide farther on ice than on a polished wooden floor; a carriage with well-oiled axles will run farther with the same push than when its axles are neglected; a top will spin longer in a china cup than on a gravel path, and longer still under the exhausted receiver of an air pump. Generally, we know, by experience and experiment, that the more completely we remove the obstacles to motion, the longer will motion continue when the impetus has once been given, and it would not be unfair to argue that if the obstacles could be removed altogether, motion would never cease. On our earth we cannot accomplish this; but in the motions of the earth itself and of other heavenly bodies, we see a proof of Newton's law. They have moved for ages, and will continue so to move under the influence of an impetus once given, their paths or orbits being traced through space in submission to the other laws of motion.

The second law of motion tells us that "change of motion is proportioned to the impressed force, and takes place in the direction of the straight line in which the force acts." It is to be noted here that a force always produces an effect, and that by the word "motion" must be understood the "quantity of motion" or "momentum," which takes into account not only the velocity but also the mass of the body; and, further, that one motion does not interfere with any other motion the body may possess or have imparted to it. This last statement may appear paradoxical, yet it will be found in accord with every day experience. It is just as easy to move in one

direction as in another in a railway carriage running at express speed, or on board a swift steamer. We are not conscious that the tremendous speed with which we are moving, in consequence of the earth's rotation, a speed equal to that of modern cannon-shot, is interfering with our freedom of action in any way; but we may hesitate before we admit that a cannon-shot fired horizontally on a level plain will strike the earth in exactly the same time as a similar shot simply dropped to the ground from the centre of the cannon. The fact is, that the ultimate result of two or more motions taking place simultaneously, is the

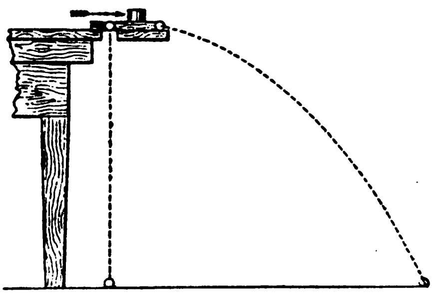


FIG. 1.

same as if the motions took place in succession. The circumstance that the cannon-shot travels at the rate of 1,500 feet per second in a horizontal direction, does not in the least interfere with the ordinary rate of falling from the height of the cannon to the ground. This fact is easily demonstrated experimentally by means of the apparatus represented in Fig. 1, from which a marble can be projected horizontally, and at the same moment another can be allowed to drop vertically, by striking sharply the spring slide which holds one ball, thus releasing it, and projecting the other horizontally. If the instrument is properly adjusted, but

one knock will be heard when the two marbles strike the floor, they will reach it in exactly the same time, though the path of one is so much longer than that of the other. Upon this law is founded the principle of the composition of motions which are taking place in two or more directions, under the influence of as many forces acting at angles to each other.

Suppose two equal forces tend to urge a body in two directions, the velocities will be equal, because the mass moved is the same and the pressure equal. Now, by the second law, the two forces do not interfere with each other, so that, taking a very minute period of time, we may suppose the motions to take place in succession, first along one line of motion till a certain point is reached, and then, from that point, in the direction of the other force and for the same time. Repeating this process, as in Fig. 2, it will be found that the body travels along the diagonal of a parallelogram constructed on the two lines of motion.

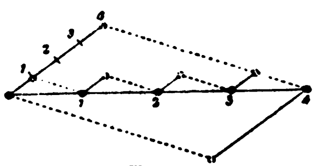


FIG. 2.

If the velocities are unequal, the length of the lines representing the direction of motion must be made proportional to the velocities; and if the velocities are not uniform, then the position of the body in equal times must be ascertained for each direction of motion, and the true place of the body found by supposing the motions to take place consecutively. The process of working this out is exhibited in Fig. 3.

The unit of measure for momentum is the unit of mass of the body, multiplied by a velocity of one foot per second. The weight of a body is a variable quantity, even on the

earth, on account of the effect of centrifugal force due to the rotation of the earth—that is to say, a pound weight which will stretch a spring balance to one pound at the Equator, will stretch it over a pound at the poles. But change of motion being proportional to the impressed force, it follows that the velocity attained in a second by the action of the weight of the body on itself, in falling freely, will be proportioned to that weight; hence the weight of the body divided by the velocity per second it produces in itself in falling freely in one second, will always be a con-

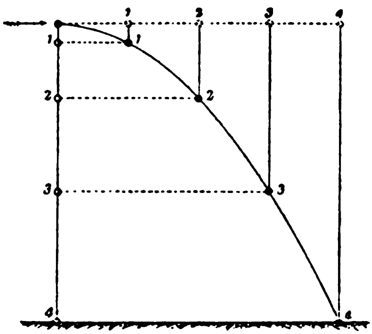


Fig. 3.

stant quantity in any place, and is called the mass, generally denoted by the letter M.

The weight of the body is usually called W, and the velocity it attains in falling freely in vacuo at the end of one second is invariably known as g; and therefore $M = \frac{W}{g}$. g is variable like W. In England it is taken approximately as $32 \cdot 2$ feet per second, or roughly as 32, so that the unit of momentum is $\frac{1}{32 \cdot 2} \times 1$ foot per second.

Supposing a force of 50 lbs. acts for one second on a

weight of 10 lbs., what will be the velocity at the end of the second? 10 lbs., acting on itself as gravity for one second, produces a velocity of 32·2 feet per second: therefore a force of 50 lbs. acting on a weight of 10 lbs. will produce five times as much motion, or 161 feet per second.

A train weighing 200 tons attains a speed of 40 miles an hour, or $58\frac{2}{3}$ feet per second in a distance of two miles. What must have been the pull of the engine all the time to produce the result? We argue in the following manner:—If the motion were uniformly accelerated, the average speed must have been 20 miles an hour, or one mile in three minutes; hence the two miles were traversed in six minutes, and the speed attained was $58\frac{2}{3}$ feet per second in 360 seconds, therefore the speed gained was ·163 foot per second. If the train had been pulled with a force of 200 tons, it would have acquired a speed of 32·2 feet per second; but, as it only attained ·163 foot, the pull must have been so much less, or only a little over one ton.

According to the second law of motion, the circumstance that a force has produced a certain velocity in a second of time does not prevent the same force producing the same effect in addition, if it acts for another second, and hence we have the fundamental equation for motion produced by a constantly acting force $v = a\,t$; that is, the velocity v, at the end of any time t, is found by multiplying the velocity a produced in the first second by the time during which the force has acted.

The formula for connecting the space passed through with the time is not so simply arrived at. Suppose a body under the influence of a constantly acting force attains a velocity of 8 feet per second at the end of the first second, then it will have passed through a distance of 4 feet. In the second second, if the force had ceased to act, the body

would, according to the first law of motion, have run over eight feet; but the force does continue to act, to produce its full effect according to the second law of motion, and adds 4 feet more to the space passed over; hence $8+4=12$ feet will be described in the second second, which, added to the distance passed over in the first second, makes 16 feet passed over in two seconds, or the space passed through during the first second multiplied by the square of the time. At the end of the second second the velocity will be $2\times 8=16$ feet; therefore, in the third second, the space passed through would be 16 feet plus the addition of 4 feet per second, or 20 feet. Adding 20 feet to the 16 feet already traversed, makes a total of 36 feet in three seconds, or 4×3^2, that is to say, the distance passed through during the first second multiplied by the square of the time; hence we have this well-known equation, for the space passed through in t seconds $S=\frac{1}{2}\,a\,t^2$, and by substitution we get

$$S=\frac{v^2}{2a}$$

$$v=\sqrt{2aS}$$

when a is the velocity produced at the end of the first second by the force.

By the aid of these equations, we can tell all about a body moving at a uniformly accelerated speed, if we know its final velocity, or the space passed through in a given time.

Take the case of the train, for example. What distance will the train travel to attain a speed of 40 miles an hour in 6 minutes? We have already seen that the pull of the engine communicated a velocity of ·163 foot per second, which is, therefore, the value of a.

The time is 360 seconds. Taking the formula $S = \frac{a t^2}{2}$ we have $S = \frac{\cdot 163 \times 360^2}{2} = 10{,}562$ feet $= 2$ miles.

Cases of accelerating forces, that is, forces acting steadily for a time, are of common occurrence; in fact, no body can be set in motion, or have its motion changed, without the action of an accelerating force; nothing starts into motion suddenly, but always by degrees, and it is a matter of common experience that to move anything with increasing velocity requires more effort than to keep up a steady speed. It is singular, therefore, that so little attention is paid by mechanics to the effect of this force in cases of reciprocating motion.

The action of an accelerating force is usually illustrated by reference to gravity. The attraction of the earth on a body near its surface is a constant force at the same place, and the velocity produced per second, 32·2 feet, is therefore made the standard by which the value of other accelerating forces is estimated.

The principles we have been examining apply equally to rotatory motion. A fly-wheel resists being brought suddenly into motion, or being suddenly stopped, just as much as a body moving in a straight line. But because the parts of a revolving body are moving at various speeds, it is necessary to find a circle in which the mean motion may be supposed to take place. This circle is called the circle of gyration, and its radius the radius of gyration. In a cylindrical disc, for example, the radius of gyration is equal to the radius of the disc divided by the $\sqrt{2}$. Having found the circle of gyration, the whole of the weight is supposed to be concentrated in it, and then the calculations are analogous to those for rectilinear motion. The circles of gyration, for

bodies of regular shape, can be arrived at by calculation. In bodies of irregular shape it can be calculated when the position of the centre of gravity is known, and the rate of oscillation about the axis has been ascertained. The radius of gyration (r) is the mean proportional between the length of an equivalent pendulum (l) and the distance of the centre of gravity from the point of suspension, (c), therefore, $l : r = r : c \because r = \sqrt{l \times c}$.

Fig. 4 is a modification of a well-known contrivance, called Atwood's machine, to demonstrate the effect of a continually acting force like gravity, or the pull of a locomotive, commonly called an accelerating force. At the top of a tall stand is a heavy brass pulley, 6 inches diameter, round which is wound a thread, one end of which is secured to it, while to the other end is attached a small weight, a little over 1 oz., so proportioned that it will fall through one foot in one second. A break, which can be released by a string, controls the motion of the pulley. On the face of the disc is a dotted circle, which represents the circle of gyration. Beside the instrument stands a metronome beating seconds. When the pulley is released, the weight falls one foot during one beat of the metronome. When the weight is pulled up again, and allowed to fall through two beats, a space of four feet is passed through. If the operation be repeated and the weight made to fall through three beats of the metronome, nine feet will be traversed. By this experiment two things are demonstrated.

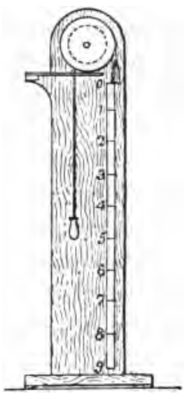


Fig. 4.

Firstly, that the velocity produced on a given load by a

force bears the same relation to the velocity produced in a body falling freely that the force bears to the weight of the load which it sets in motion.

The pulley weighs 1·95 lb. The circle of gyration is 4·24 inches diameter. One foot fall of the weight corresponds, therefore, to 1 ft. $\times \frac{4 \cdot 24 \text{ in.}}{6 \text{ in.}} = \cdot 707$ foot described by a point in the circle of gyration, and therefore the velocity acquired at the end of one second is $\frac{2\,S}{t^2} = \frac{2 \times \cdot 707}{1^2}$ $= 1 \cdot 414$ feet. The load set in motion by the weight is its own weight, added to that of the disc concentrated in the circle of gyration. Calling the weight x lbs., it will bear the same relation to the load 1·95 lb. + x lb. as 1·414 feet bears to 32·2 feet, the velocity acquired in one second by x falling freely by itself.

$$\frac{x}{1 \cdot 95 + x} = \frac{1 \cdot 414}{32 \cdot 2}$$
$$x = \cdot 09 \text{ lb.}$$

acting at the circle of gyration, or

$$\cdot 09 \times \frac{4 \cdot 24''}{6''} = \cdot 064 \text{ lb., or } 1 \cdot 02 \text{ oz.}$$

acting at the periphery of the pulley.

Secondly, the apparatus demonstrates that the spaces passed through under the influence of a uniformly acting force are as the squares of the times.

When a body which is moving with a given velocity has to be stopped, the reverse action takes place; the force required to retard motion is exactly the same as that required to produce it, and, therefore, to stop a train of 200 tons weight going at the rate of 40 miles an hour within

a distance of two miles would require the breaks to exert an opposing push of one ton.

It follows from these considerations that the shorter the time or space in which motion has to be set up or stopped, the greater must be the accelerating or retarding force or pressure. In the case of one train coming into collision with another, the space is so short that the force increases to a point which shatters the carriages.

A rifle-bullet can be stopped in about eight feet without injury to itself by being fired into bran; but fired against an iron target, the space in which the motion is stopped, which is less than the length of the bullet, is so small that the retarding pressure rises to a pitch which completely destroys it.

Newton's third law of motion is, "To every action there is always an equal and contrary reaction." This law applies equally to statical pressures, and to momentum or quantity of motion. The reaction may consist of pressure, friction, resistance of the air, or acceleration; but whatever may be the nature of the reactions, the sum of their momenta is equal to that of the moving force.

The train we have already used to illustrate our reasoning will serve again. The power of the engine is resisted, we have seen, by a pull of one ton due to acceleration. In addition to this, there are the friction of the axles and of the rails, which may be taken at 10 lbs. to the ton weight of the train, or 2,000 lbs., and a variable resistance due to friction against the air, to the adverse pressure of parting it, and to the wind; all these together form the reaction to the action of the locomotive while the speed of 40 miles an hour is being attained. As soon as that has taken place, and the motion becomes uniform, the accelerating force ceases to act, and friction with resistance of the

atmosphere alone remain, hence the work of the locomotive becomes much easier.

The term "work" of the locomotive has been used. This word requires closer examination. By the term "work" in mechanics is meant the force applied to a body multiplied by the space gone over in the direction in which the force is producing motion. The unit of work is one pound pull or pressure acting through a space of one foot, and hence called a foot-pound. The accelerating force of the train, for example, was one ton, or 2,240 lbs., acting through two miles, or 10,560 feet, hence the work done in bringing the train from a state of rest to a speed of 40 miles per hour was 10,560 ft. × 2,240 lbs. = 23,654,400 foot-pounds.

It is frequently more convenient to speak of the *rate* at which work is being done than of the total work performed. The unit of rate of work, for large quantities, has been taken as 33,000 foot-pounds per minute, and is called a horse-power. The work of getting up the speed of the train occupied six minutes; hence the rate of work was

$$\frac{23{,}654{,}400 \text{ foot-pounds}}{6 \text{ minutes}} = 3{,}942{,}400 \text{ foot-pounds per minute},$$

or, dividing by 33,000 foot-pounds, we get 119·4 horse-power, which the locomotive exerted in producing the accelerated motion of the train.

In addition to the term "work," we have another expression, "energy," which means the capacity for doing work, and it is of two kinds.

"Potential," the power of doing work latent in an advantageous position. For example, the water in a lake high up among the hills has a very different value from the same water fallen to the sea level, because, in the former case, it can, by its fall, be employed to do useful

work; in the latter it cannot. The chemical constituents of coal and the oxygen of the air are the same after as before combustion, they are only differently arranged with respect to each other, and yet the products of combustion are valueless, whilst in the form of coal and air they are necessaries of life, because they form a store of potential energy. The heavenly bodies moving at uniform velocities for ever are instances of potential energy; they are doing no work so long as they are moving steadily; but if the motion of any one of them were opposed by some external resistance, its velocity would be diminished in proportion to the amount of resistance offered, and work would be given out. The steam pent up in a boiler, or compressed air, are also instances of potential energy.

The other form is that of "energy of motion," or "kinetic energy." Water falling and working a water mill is an instance of this; the action of steam on the piston of a steam-engine, an animal drawing a load, &c. The sum of the potential and kinetic energies in any body is a constant qnantity. Water that has fallen to the sea level has lost all the energy it may once have possessed; it has expended it in producing some kind of mechanical work. Suppose that we had an available fall of water of ten feet working a mill. Every 330 gallons falling in one minute would produce 33,000 foot-pounds of work, or one horse-power; hence the potential energy of each gallon of water is $\frac{1}{330}$ of a horse-power. But after the water has passed through a well-arranged motor, it flows sluggishly away to the sea, having yielded up nearly all its energy, in the form of energy of motion, to the machinery it was intended to bring into activity. But suppose that, from circumstances or bad arrangement the water flowed away at a

rapid rate, say ten feet per second, this would correspond to $\frac{10^2}{64 \cdot 4} = 1 \cdot 55$ feet of vertical fall; energy due to that height, therefore, remained in the water when it left the motor, and was wasted, making a loss of $15\frac{1}{2}$ per cent.

When we know the weight and the velocity with which a body is moving, we can easily calculate its energy or power of doing work. Take the case of a 6-inch cannon-shot, weighing 100 lbs., leaving the muzzle of a gun with 1,500 feet per second velocity, acquired in a barrel 15 feet long; and let us farther suppose that the motion in the gun is uniformly accelerated. Because 1,500 feet velocity was acquired in a distance of 15 feet, the velocity at the end of a second would have been, had the force continued to act, $a = \frac{v^2}{2 \times 15} = \frac{1{,}500^2}{30'} = 75{,}000'$, and the pressure to produce such a velocity would have been $\frac{100 \text{ lbs.}}{32 \cdot 2} = \frac{x}{75{,}000 \text{ ft.}} \therefore x = \frac{100 \text{ lbs.} \times 75{,}000 \text{ ft.}}{32 \cdot 2 \text{ ft.}} = 232{,}919$ lbs., or nearly 104 tons. This would correspond to a mean pressure of $3 \cdot 7$ tons to the square inch of the powder gases, and the work done would have been 104 tons $\times$ 15 feet = 1,560 foot-tons.

We can arrive at the result in a quicker manner. The shot starting from the muzzle of the gun, if directed vertically upwards, would rise to a height $\frac{v^2}{2\,g} = \frac{1{,}500^2}{64 \cdot 4} =$ 34,938 feet. If it fell from that height it would do work equivalent to its own weight of 100 lbs., which is the force impelling it, multiplied by the distance fallen: or 3,493,800 foot-pounds, equal to 1,560 foot-tons, the same result as we obtained before, hence we have the general

expression for the energy of a moving body $= \frac{W}{2g} v^2$ or the square of the velocity multiplied by half the mass. Energy must not be confounded with momentum or quantity of motion; the former has foot-pounds for its unit, and varies as the square of the velocity; the latter has mass multiplied by one foot per second as its unit, and varies as the velocity.

Another illustration of the convertibility of potential and kinetic energy we have in a jet of water. A fountain having a jet $\frac{3}{4}$ inch in diameter, is supplied by a reservoir 40 feet above the jet through a 3-inch pipe. According to well-known laws of hydraulics, the velocity of the water issuing from the jet will be the same as that attained by a body falling freely from the surface of the reservoir to the level of the jet, and we know that could the resistance of the air and frictions be abolished, such velocity would be competent to carry each particle of water back again to a height equal to the level of the water in the reservoir. The velocity due to a height of 40 feet from the influence of gravity will be $8\sqrt{40} = 50 \cdot 56$ feet per second, and the kinetic energy of each pound of water issuing from the jet would be $= \frac{1 \text{ lb.} \times 50 \cdot 56^2}{64 \cdot 4} =$ 40 foot-pounds. The potential energy of 1 lb. of water lying 40 feet above the jet is also 40 foot-pounds, so here we have a case of complete conversion.

But the area of the 3″ supply pipe is 16 times that of the jet, hence the velocity of the water in it will be only $3 \cdot 18$ feet per second, and the kinetic energy of 1 lb. $=$ $\frac{1 \text{ lb.} \times 3 \cdot 18^2}{64 \cdot 4} = 0 \cdot 15$ foot-pound; hence in any portion of the pipe the pressure will be less than that due to

the column of water above it by 0·15 foot, because the sum of the potential and kinetic energies must be constant. This pressure represents the accelerating force which imparts to the still water in the reservoir the velocity with which it moves in the pipe, and is called the "head of flow."

The case of converging and diverging jets are instructive illustrations.

In a converging jet, the velocity of the water is constantly increasing, until at last, when it leaves the jet, it is evident that there is no pressure on the pipe at all,

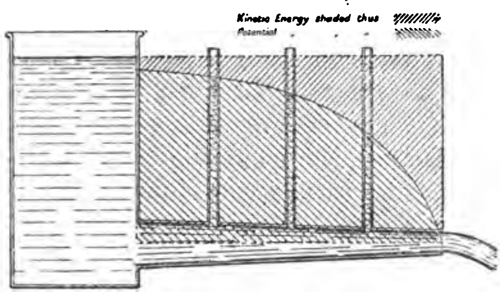


Fig. 5.

because the jet does not spread out laterally, all the potential energy has become kinetic: hence, in a converging jet, the pressure on the sides of the pipe decreases continually, and the pressure at any point may be ascertained by deducting the kinetic energy at that point of the cone from the total potential energy.

Fig. 5 represents a converging jet issuing from a tank.

If glass tubes be inserted along the jet, the water will be found to stand lower the narrower the jet becomes. Suppose that the area of the pipe at the middle be double that at the point, the velocity of the water will be one

half, and because the head of flow $= \frac{v^2}{64 \cdot 4}$ it varies as the square of the velocity, and hence the head of flow will be one-fourth that producing the velocity at the discharge end of the jet. By making a similar calculation for each tube, the height of the water in each may be arrived at, and a line drawn, touching the water-levels in the tubes, will form a regular curve, all heights outside of which will represent kinetic energy, and all inside statical pressures in the tube, the sum of the two being always equal to the total pressure.

In diverging pipes, when the enlargement of diameter is sufficiently gradual to permit of the fluid always filling the pipe, which it tends to do by reason of its viscidity and adhesiveness to the material the pipe is made of, the velocity with which each particle of fluid moves must continually decrease, and its kinetic energy must also decrease in proportion to the square of the decreased velocity. The energy with which the fluid was endowed, as it issued from the narrow end, or origin, of the tube, must therefore be converted partly into the potential energy represented by a tendency to push aside the atmospheric pressure against the open end of the tube, and partly to tear asunder the cohesion of the fluid, and break the stream up into slices. Both tendencies are manifested by an increased discharge from the pipe, because the atmospheric pressure acting on the surface of the liquid above the narrow end of the pipe, augments the flow in proportion as the retardation of the fluid towards the open end cuts off the pressure of the atmosphere from that side. The whole of the conical tube is in partial vacuum from the large end backwards, the vacuum, which represents the potential energy, increasing as the narrowed part of the

tube is approached, on account of the great mass of water operating to balance the atmospheric pressure, and call into play the cohesive force of the fluid.

Fig. 6 represents a diverging jet by means of which water flows out of a cistern. The vertical lines bounded by the parallelogram above the pipe, indicate the statical pressure of the water, supposing that the outer end of the jet were closed, while the vertical lines, bounded by the curve, represent the degree of vacuum which the jet will produce when the water is permitted to flow.

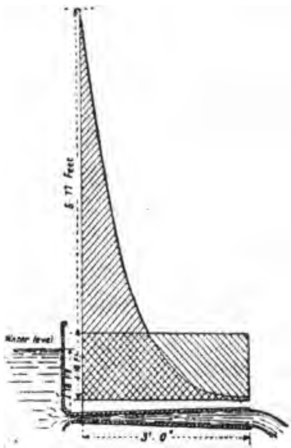


Fig. 6.—Lowell Diverging Pipe, J. B. Francis.

The phenomenon may also be explained in the following manner:—Imagine the fluid in the diverging pipe to be cut up into slices, at right angles to the axis, then, because the motion is continually retarded, the pressure on the front of each slice must be greater than at the back, and consequently the pressure in the narrow part of the tube must be less than in the wide part. But the pressure against the widest part is that of the atmosphere, hence that in the narrower parts must be less, that is, a partial vacuum.

The tendency of the fluid to break up into slices is made manifest by the pulsations which, with air, produce sound, as in a trumpet, and with liquids generate undulations which may be observed when the diverging pipe is submerged.

In Mr. Francis' valuable work on the hydraulic experiments at Lowell, in the United States, will be found a very minute account of the behaviour of a diverging jet discharging water. He experimented with a pipe of which the sides diverged at an angle of 5° to each other, and had the orifice at the smaller end one-tenth of a foot in diameter. He found that there was no increase of discharge after the pipe had been extended to a length of 3 feet, with an outer diameter of ·32 foot, when the best results were obtained, namely, a discharge nearly two-and-a-half times greater than that due to the head. In Fig. 6 one of the experiments has been represented. The head of water over the centre of the pipe was only 1·18 feet, the velocity of discharge corresponding to which is 8·7 feet per second, but the actual velocity proved to be 21·15 feet per second, corresponding to a head of 6·95 feet. At the open end of the pipe the velocity fell to 2·13 feet per second, corresponding to a head of ·07 foot, so that during the passage of the water through three feet of pipe the kinetic energy of each pound had been reduced to nearly the $\frac{1}{200}$ part. The average kinetic energy of the contents of the pipe was ·676 foot-pound per pound of water. The total potential energy of each pound of water was that due to the head under which the flow had taken place, namely, 1·18 feet, for that was the only motive force; hence the potential energy available for relieving the pressure on the discharge side of the orifice at the smallest part was 1·18 − ·674 = ·506 foot-pound per pound of water, corresponding to a head of ·506 foot.

The contents of the pipe weigh 5·7 lbs., therefore the total available potential energy was 5·7 lbs. × ·506 foot = 2·88 foot-pounds employed in relieving the back pressure against an orifice ·1018 foot diameter, and ·00814 square

foot area, hence the column of water which this would have represented was $\frac{2 \cdot 88 \text{ foot-pounds}}{62 \cdot 2 \text{ lbs.} \times \cdot 00814} = 5 \cdot 69$ feet. The actual extra head induced was $5 \cdot 77$ feet, which includes the friction in the pipe of which no account has been taken.

In Fig. 7 the diagram is extended so as to make the length of the base proportional to the weight of water in the pipe, which of course it is not in Fig. 6. The parallelogram therefore represents correctly the total potential energy of the pipe full of water, which is $6 \cdot 73$ foot-pounds, while the area bounded by the curve represents the portion

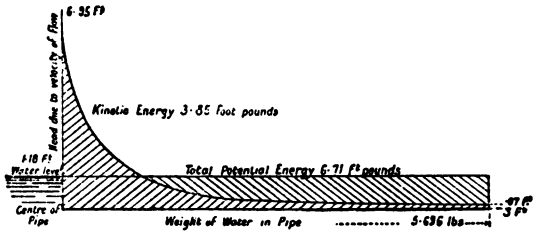


FIG. 7.

rendered kinetic, and is equal to $3 \cdot 85$ foot-pounds; the difference, $2 \cdot 88$ foot-pounds, is available to press back the atmosphere, and cause the partial vacuum in the narrow part of the tube.

The ancient Romans, though they did not understand the principles on which diverging pipes acted, were well aware of the property they possessed in increasing the flow of water, and made use of it to get an undue supply from the gauge pipes of the public aqueducts.

It is immaterial what fluid we employ to produce the effects above described. Fig. 8 represents a conical pipe, *a*, through which a current of air can be forced

by means of a bellows. The base of the diverging mouthpiece is connected to a syphon water-gauge; as soon as the air is made to flow, the column of water in the gauge rises, indicating the formation of a partial vacuum.

If a plain parallel pipe be substituted for the cone, a slight pressure instead of a vacuum declares itself in the gauge: that pressure is the measure of the friction of the air against the sides of the pipe.

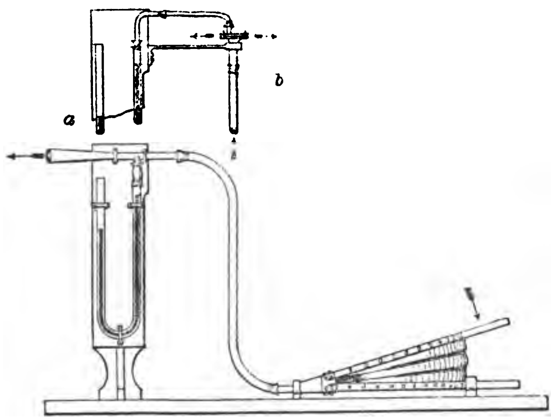


FIG. 8.

If a pipe be made to terminate in the centre of a flat disc as *b*, and if another disc of any light material be laid over it, so as to cover symmetrically the orifice of the pipe, then if a stream of any liquid or gas be caused to flow through the pipe, it will be found impossible to blow the covering disc off, no matter how great the pressure employed. The disc will rise a little, the fluid will issue all round; a rapid pulsation, which, if the pressure be sufficient, will declare itself in a musical sound, will take place; but

it will be impossible to blow the disc off. The reason is that the fluid entering the central aperture spreads out radially, and the least rise of the disc makes the area of the annular orifice by which it escapes all round the disc greater than that of the pipe; hence the velocity of the fluid and its kinetic energy are diminished by being expended in pushing aside the atmosphere, and so keeping up a partial vacuum in the centre of the disc. But this is a state of unstable equilibrium, the disc tending always to rise higher, but in so doing reducing the velocity of the escaping fluid, and increasing the vacuum, and consequently the pressure tending to hold it down, hence pulsations, more or less rapid, arise. By connecting the centre of the disc to the syphon gauge, the existence of a vacuum is at once indicated.

When a body is moving under the influence of two forces the resultant motion is of such magnitude that there is no loss of energy, because energy is as indestructible as matter. Suppose a body W, Fig. 9, to be moving horizontally at a uniform rate of 3 feet per second, and at the same time being impelled vertically by a constantly-acting force of such magnitude that one foot of space is described from rest in the first second. Then because $\frac{2\,S}{t} = v$ the velocity at the end of the first second will be 2 feet per second, which will represent the rate of acceleration. At the end of two seconds, the velocity will be $v = at = 2$ feet $\times$ 2 seconds $= 4$ feet per second, so that when the body has reached the position A at the end of 2 seconds, A B $= 3$ feet will represent the horizontal velocity and A C$=4$ feet the vertical. Constructing a parallelogram, the diagonal A D will indicate both the direction and magnitude of the motion, because the energy

of the horizontal motion is $\frac{W}{2g}$ A B^2, and that of the vertical $\frac{W}{2g}$ A C^2, the resultant velocity, if no energy is lost, must be $\frac{W}{2g}(A\ B^2 + A\ C^2)$. But, from the properties of the triangle, we know that $A\ D^2 = A\ B^2 + A\ C^2$, hence $\frac{W}{2g}$

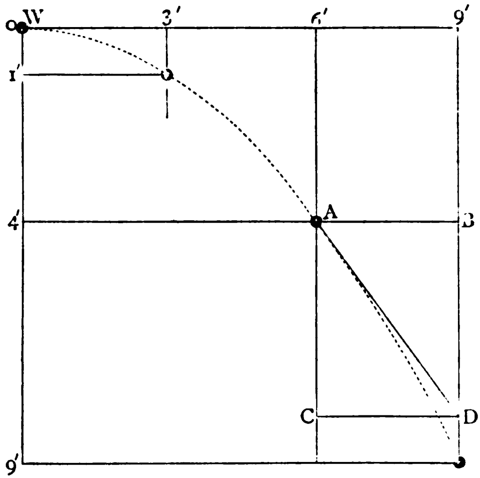


Fig. 9.

A D^2 represents the total energy, and therefore A D is the actual velocity with which the body is moving when it reaches A.

In the parts of machinery which have a reciprocating motion, the weight moved passes during each stroke from a state of rest to a condition of maximum velocity and relapses again, at the end of the stroke, into a momentary state of rest. The most familiar instances of this kind of motion

are found in the movements of pistons joined by means of connecting rods to cranks.

Fig. 10 represents such an arrangement. C P is a crank two feet long; P E a connecting rod ten feet long, and 0 to 12 is the stroke of the piston of a steam engine or pump. The crank pin P is supposed to move with a uniform velocity of 5 feet per second from 0 to 12. Dividing the semi-circumference into 12 parts, corresponding each to 15° and numbering them, the corresponding positions of the piston can be ascertained by geometrical construction, or more accurately by calculation.

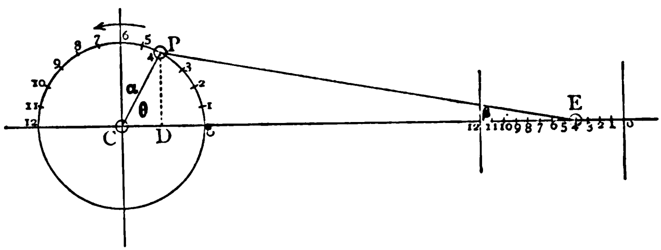


FIG. 10.

P E being five times the length of the crank C P therefore

$$P\,D = C\,P \text{ sine } \Theta = 5\,C\,P \text{ sine } \beta \therefore = \text{sine } \beta = \frac{\text{sine } \Theta}{5}$$

from which the values of the angle β, which the connecting rod makes with the centre line, may be derived. Next $C\,E = C\,D + D\,E = C\,P \cos\Theta + 5\,C\,P \cos\beta = C\,P\,(\cos\Theta + 5\cos\beta)$ from which equation the distance of the piston from the centre of the crank shaft may be determined. The velocity of the piston (v) at any point of the stroke may be calculated by the following formula

$$v = \text{velocity of crank pin} \times \frac{\text{sine }(\Theta + \beta)}{\cos\beta}.$$

The rate of acceleration and retardation of velocity (v) is found by the equation

$$\text{acceleration} = -\,a\,\omega^2\left\{\cos\theta + \frac{a\,(b^2\,(1-2_2\ \text{sine}\ ^2\theta) + a\ ^2\text{sine}\ ^4\theta)}{(b^2-a^2\ \text{sine}^2\theta)\ ^{\frac{3}{2}}}\right\}$$

where

ω = the velocity of a point in the crank one foot from the centre of shaft.

a = length of crank.

b = length of connecting rod.

This expression becomes very simple at the ends of the stroke where $\Theta = 0$. Thus

$$\text{At point } 0 = -\,a\,\omega^2\left(1+\frac{a}{b}\right)$$

$$\text{At point } 12 = a\,\omega^2\left(1-\frac{a}{b}\right)$$

In working out the equation for the various points selected, it will be found that the sign changes from negative to positive near the middle of the stroke, which means that the pressure producing acceleration in the first part of the stroke, represents resistance to the motion of the piston, and in the second part implies assistance to that motion.

Assuming the crank pin to move at a uniform rate of five feet per second, the following table gives the details of the particular case selected :—

1	2	3	4	5	6	7
Point.	Angles.		Distance of piston from end of cylinder.	Velocity of piston in feet per second.	Acceleration of piston in feet per second.	Pressure to produce acceleration in 18660 lbs.
	θ	β				
						lbs.
0	0	0	0·feet	0·	− 15·	− 8692
1	15°	2°·58′	0·082	1·545	− 14·25	− 8257
2	30°	5°·44′	0·318	2·935	− 12·10	− 7012
3	45°	8°·8′	0·678	4·040	− 8·86	− 5136
4	60°	9°·58′	1·152	4·770	− 4·98	− 2883
5	75°	11°·8′	1·668	5·080	− 1·036	− 600
6	90°	11°·33′	2·204	5·	+ 2·55	+ 1479
7	105°	11°·8′	2·706	4·574	+ 5·445	+ 3155
8	120°	9°·58′	3·160	3·891	+ 7·525	+ 4361
9	135°	8°·8′	3·514	3·030	+ 8·79	+ 5094
10	150°	5°·44′	3·782	2·065	+ 9·55	+ 5534
11	165°	2°·58′	3·946	1·043	+ 9·90	+ 5737
12	180°	0	4·	0	+ 10·	+ 5795

In Fig. 11 the results obtained have been represented graphically. 0 to 12 is the stroke of the piston. The

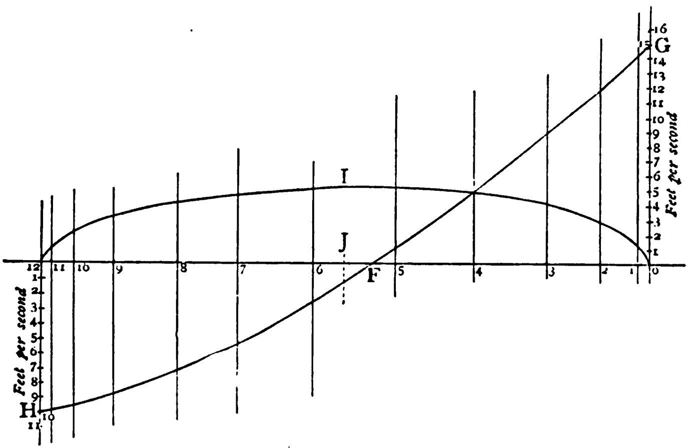


FIG. 11.

intermediate numbers correspond to the points in the path of the crank represented in Fig. 10. The ordinates between

the curve 0 I 12 and the centre line 0—12 represent the velocities of the piston derived from column 5 in the table. The distances between the curve G F H and the centre line represent the accelerations and retardations derived from column 6. It will be noticed that the line G F H cuts the centre line in F a little before half stroke, at which point there is no acceleration, because the velocity of the piston has reached its maximum. The crank has then moved about 79°, and the point F is 1·842 feet from one end of the cylinder, and therefore 2·158 feet from the other end. The velocity of the piston is 5·099 feet per second.

Now the accelerations correspond to g in gravity, hence if W be the weight moved, then $\frac{W}{g} = \frac{F}{\text{acceleration}}$.

$$\therefore F = \frac{W \times \text{acceleration}}{g} = \text{the pressure}$$

necessary to produce the change of velocity in the weight W at any part of the stroke, hence the ordinates to the curve G F H are proportional to the pressures; the areas G F O and H F 12 are proportional to the work done in accelerating the motion of the weight, and in again retarding it; and, since energy is indestructible, the work of acceleration must just balance that of retardation—that is, the two areas must be equal. By plotting the curves carefully and measuring their areas such will be found to be the case.

Moreover, the weight W has had a velocity of 5·099 feet per second imparted to it, hence its potential energy opposite the point F will be

$$\frac{W \times 5{\cdot}099^2}{64{\cdot}4}$$

and this must equal the work of acceleration and retardation, or the area of the two surfaces G F O and H F 12.

Suppose the crank to be driving a pump with a barrel one square foot in area, and suppose about 300 feet of pipe of the same area be connected to the pump, then the total weight of water moved may be taken at 18,660 pounds =W.

Measured from the diagram, the mean rate of acceleration proves to be 7·024 feet per second, and the maximum speed is reached in 1·842 feet, hence the work done in getting up the speed is

$$\text{Work} = \frac{7\cdot024' \times 1\cdot842' \times 18{,}660 \text{ lbs.}}{32\cdot2} = 7{,}498 \text{ foot-pounds}$$

and the work of retardation, the mean velocity measured from the diagram being 5·963 feet per second during 2·158 feet of the stroke,

$$\text{Work} = \frac{5\cdot963' \times 2\cdot158' \times 18{,}660 \text{ lbs.}}{32\cdot2} = 7{,}457 \text{ foot-pounds}$$

The energy potential in the water at its greatest speed—

$$\text{Energy} = \frac{18{,}660 \times 5\cdot099^2}{64\cdot4} = 7{,}534 \text{ foot-pounds.}$$

The results agree very closely, considering that the measurements were taken from but a small diagram.

Column 7 in the table gives the pressures throughout the stroke. It will be noticed that at the beginning of the stroke, without any lift whatever of the water, a pressure of 8,692 pounds has to be exerted to start the water into motion, and at the end of the stroke 5,795 lbs. are pressing against the piston in the opposite direction. It is these pressures so frequently ignored and neglected by

engineers which cause the knocks at the turn of the stroke so common and troublesome in pumps, for the transition is from a push of 5795 lbs. in one direction to a push of 8692 lbs. in the opposite sense. The best way to obviate the evil effects of these pressures is to place capacious air vessels on both sides of the pump; this lessens the weight, to which velocity has to be communicated quickly, to that of the water between the air vessels and the pump, the air in the vessels constitutes springs which yield to the sudden pressures in order to expand slowly and expel the water at a nearly uniform speed during the entire stroke.

Suppose the whole of the pipe to be on the suction side of the pump, the pressure of acceleration per square inch will be $\frac{8692 \text{ lbs.}}{144 \text{ sq. in.}} = 60 \cdot 3$ lbs., or four times that of the atmosphere; hence, at the turn of the stroke, the pressure of the atmosphere would be incompetent to compel the water to move as fast as the piston; a waterless space behind the piston, which would be a vacuum, would be formed, and at length when the water did catch up the piston, it would strike against it, like it does in a water-hammer, with a metallic ring and with destructive force. At the end of the stroke, if there were but a small lift, less than $\frac{5795 \text{ lbs.}}{144 \text{ sq. in.}}$ $= 40 \cdot 2$ lbs. per square inch, or 92 feet, the water pressure due to retardation would open the valves, the water would push past the piston, and the pump would deliver more than its own volume. Such an occurrence is by no means unusual with fast running pumps, fitted with long pipes and working at suitable lifts.

In the case of steam-engines the weight of the reciprocating parts must be taken account of, if smooth motion be aimed at. It is obvious that great pressure is needed at

the beginning of the stroke to impart the necessary acceleration, and on the other hand a low pressure is desirable at the end of the stroke, so as to allow the retarding pressure to expend itself in urging the piston forward, hence, the expansive use of steam, instead of producing irregular motion, as is commonly supposed, is the best possible means of compensating for the forces which we have been considering. If the rate of expansion be not such as to compensate for the acceleration and retardation of the moving parts, then the work must be done by the fly-wheel, that is to say, the momentum of the fly-wheel must help to drag the piston to its full speed at the beginning of the stroke, and oppose its motion at the end; in both cases a sudden reversal of pressures takes place, and a consequent knock in the machinery is the result. Great practical advantage is derived from "cushioning," and "lead." By the former expedient the exhaust passage is closed before the end of the stroke, the imprisoned steam is compressed, and by that means neutralizes the momentum of the moving parts without calling on the fly-wheel for help; and by "lead" is meant the admission of steam a little before the beginning of the stroke, for the purpose of giving aid to the cushioning in curbing the motion of the piston. The cushioning tends to restore the steam left in the clearances of the cylinder and ports to the initial boiler pressure, and by that means to obviate the waste of steam which would otherwise arise, and by so doing utilizes the work of retardation, without strain to the machinery.

Suppose a steam-engine, having a 12-inch cylinder by 2 feet stroke, be running at 200 revolutions per minute, and let its connecting rod be 5 feet long, and its reciprocating parts weigh 300 lbs.

The acceleration at the beginning of the stroke will =

$$- a\,\omega^2 \left(1 + \frac{a}{b}\right) = \omega^2 \left(1 + \frac{1}{5}\right) \text{ where}$$

$$\omega = \frac{6 \cdot 283' \times 200 \text{ revol.}}{60 \text{ minutes}} = 20 \cdot 944 \text{ feet per second,}$$

maximum acceleration = $- 20 \cdot 944^2 \times 1 \cdot 2 = - 526{\cdot}4$ feet per second and the corresponding pressure

$$= \frac{300 \text{ lb.} \times - 526 \cdot 4 \text{ feet}}{32 \cdot 2 \text{ feet}} = - 4903 \text{ lbs.}$$

which divided over the area of the piston gives 43·4 lbs. per square inch, expended in overcoming the inertia of the reciprocating parts.

Next, the maximum retardation at the end of the stroke

$$= a\,\omega^2 \left(1 - \frac{a}{b}\right) = 20 \cdot 944 \times {\cdot}8 = 350 \cdot 8 \text{ feet,}$$

and the corresponding pressure

$$= \frac{300 \text{ lbs.} \times 350 \cdot 8 \text{ feet}}{32 \cdot 2 \text{ feet}} = 3269 \text{ lbs.}$$

equivalent to 28·9 lbs. per square inch.

Suppose the steam to be at 100 lbs. pressure and expanded four times, the final pressure would be

$$\left(\frac{100 \text{ lbs.} + 15 \text{ lbs.}}{4}\right) - 15 \text{ lbs.} = 13 \cdot 75 \text{ lbs.}$$

The pressure on the crank pin at the beginning of the stroke would be 100 lbs. – 43·4 lbs. = 56·6 lbs. per sq. inch, and at the end of the stroke 13·75 lbs. + 28·9 lbs. = 42·7 lbs., or in the ratio of 1·3 to 1.

Had there been no expansion the pressures would have been as

$$
\begin{array}{rcl}
100 \text{ lbs.} - 43 \cdot 4 \text{ lbs.} & : & 100 \text{ lbs.} + 28 \cdot 9 \text{ lbs.} \\
56 \cdot 6 & : & 128 \cdot 9 \\
1 & : & 2 \cdot 3
\end{array}
$$

The pressure would have been highest at the end of the stroke.

We must next consider the laws of impact. The consequences of impact vary according to the hardness or elasticity of the bodies striking against each other. If the bodies are elastic and do not permanently change their forms from collision, the whole of the energy of the striking body is expended in producing motion in the body struck. If the bodies are imperfectly elastic, a portion of the energy is expended in distorting or breaking up the structure of one or both bodies.

During the moment of impact of elastic bodies, that is to say, in the very brief time during which the bodies are in contact, the sum of the momenta of the two bodies is the same as it was before the impact took place. In perfectly elastic bodies, the work done in resisting compression during the first period of impact is equal to that given out during the second period, when the body regains its shape, and the energy so restored is divided between the two bodies, which continue to move, but with altered velocities; there is thus no conversion of kinetic energy into any other form in the impact of perfectly elastic bodies. This is proved experimentally by the impact of two elastic balls of the same weight, suspended from a frame. The ball which strikes is brought to rest, but imparts all its energy to the ball struck, because the rebound is exactly equal to the blow.

When inelastic bodies strike each other, they do not recoil, but move on together, and the velocity of the two is found by dividing the sum of their separate momenta by the sum of their masses.

$$V = \frac{M_1 V_1 + M_2 V_2}{M_1 + M_2}$$

Thus a soft body weighing 10 lbs., if it strike a body of the same weight at rest, the two will move on at half the velocity. The energy of motion in the mass of 20 lbs. will, however, be only half that of the single body at a higher velocity, because energy varies as the square of the velocity and directly as the weight, hence double the weight and half the velocity will yield only half the energy, the remaining half having been expended in distorting the two bodies. By substituting two lead balls for the elastic ones hanging in the frame, and causing one of the lead balls to strike the other, the two will swing together, and if the surfaces be examined, a bruised and distorted place will be found on each ball. In the impact of elastic bodies, because none of the energy is absorbed in permanently changing the shape of the bodies, and because energy is indestructible, the sum of the energies before and after collision remains the same, that is to say, the sum of the masses of the two bodies multiplied by the squares of their respective velocities remain the same after as before the impact.

Suppose a ball weighing 10 lbs. strikes with a velocity of 20 feet per second, another ball weighing 15 lbs. moving in the same direction at the rate of 5 feet per second. The result would be that the velocity of the 10 lb. ball will drop to 2 feet per second, while the heavier ball will shoot forward at the rate of 17 feet per second, and the

sum of the energies of motion both before and after collision will be the same, that is to say, 67·9 foot-pounds.

When an elastic body strikes a fixed elastic substance, the body will rebound with the same velocity with which it struck.

In oblique impacts, that is to say, when the lines of motion are inclined to each other, the velocities have to be resolved in directions parallel, and at right angles to, the direction of motion of the body struck; then, according to the second law of motion, each component of the force will produce its full effect, as if no previous motion existed.

When an elastic body strikes an elastic plane surface at

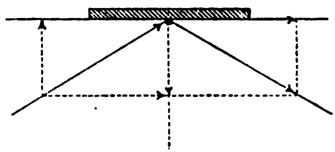


FIG. 12.

an angle, the direction of the blow resolves itself into motion along the plane, and at right angles to it. According to the first law of motion, the velocity along the plane will continue uniform, while we have just seen that an elastic body striking a fixed one at right angles rebounds with the same velocity with which it struck; hence the conditions are exactly reversed with respect to the motion at right angles to the plane, but unaltered with respect to the motion along the plane, and therefore the body will glance off at the same angle as that at which it struck.

In a game of billiards, the laws of impact are illustrated in endless variety, although the conditions are unfavourable, because the balls and cushions are not perfectly elastic.

The balls often have a twist, while the friction of the table and resistance of the air interfere with the uniformity of velocity.

When we speak of perfectly elastic substances, we do not mean those which, like india-rubber, have a great range of elasticity, but those like glass and hard metals, which cannot be deformed, because their elastic limits approach very nearly to the ultimate strength or stress producing rupture.

It has been stated that, in the impact of elastic bodies, no energy is expended in the deformation of the bodies, but that all is employed in producing visible motion. This is not strictly correct. When the balls strike against each other a sound is heard, that sound is caused by the vibration of the substance of the balls communicated to the ears through corresponding vibrations of the air; the energy necessary to produce these secondary motions is lost, so far as any effect it can produce on the visible motion is concerned. If the impacts were sufficiently frequent, the work expended in internal vibration of the balls would be competent to stop the motion were all other resistance abolished.

This consideration is of importance in the theories relating to the ultimate structure of matter, and was dwelt upon at some length by Sir William Thomson in his recent address to the British Association.

CHAPTER II.

HAVING briefly investigated the laws of motion, the principle of work, the meaning of energy, the theory of impacts, and having made some practical applications of the laws discussed, we proceed to inquire into the principles involved in oscillations or vibrations; a full investigation of wave theories, however, being far beyond the scope of this work. Oscillation or vibration, then, is motion propagated through the substance of a body by short excursions of the molecules of the body to and fro, either in direct lines or in closed curves. A familiar illustration of an oscillating motion is a pendulum; and it is also an instance of the mutual relations between kinetic and potential energies. The moving force is gravity. The bob of the pendulum falls from the highest point to which it has been raised to the lowest point, and in so doing the whole of the potential energy with which it had been endowed, just when allowed to drop, is converted gradually into kinetic energy, and this notwithstanding that its path is not free, but constrained by the rod of the pendulum; but this constraint, according to the second law of motion, does not interfere with the action of gravity. The kinetic energy with which the bob is endowed at its lowest point is competent to carry it again up to the same height as that from which it fell, and in doing so, the energy is gradually changed till again it all becomes potential.

Were it not for the friction of the attachment of the pendulum-rod, and the resistance of the air, the oscillation, once set going, would continue for ever, and at a uniform speed, because the force causing it is constant. In clocks, where advantage is taken of this property of a pendulum, the retarding forces are counteracted by the escapement, a mechanical contrivance set in motion by a wound-up weight or spring, which gives the pendulum a little push during each oscillation.

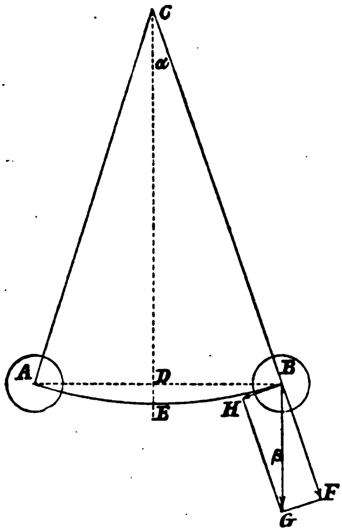


FIG. 13.

Let A C, B C (Fig. 13), be the two extreme positions of a pendulum. The force acting on the bob is its weight represented in magnitude and direction by the vertical line, B G. This force is resolved into B F acting in the direction of the rod, and into B H at right angles to it, and therefore tangentially to the arc described. Now, because B G is parallel to C E, and H G to C B, therefore the angle β is equal to the angle a. H B, which represents the magnitude and direction of the impelling force throughout the swing, is proportional to the sine of β, and therefore to the sine of a, and consequently to D B. Now if any elastic rod fixed at one end be pulled to one side, the resistance to deflection for moderate distances will be proportional to the amount of deflection or to the length D B, and therefore such a rod,

if let go, will vibrate according to the same law as a pendulum; and the general equation for the maximum velocity attained applies to all vibrating bodies, namely—

$$v = \frac{\mathrm{D\,B} \times 2\,\pi}{\mathrm{T}}$$

Where T is the time of a complete vibration or cycle and D B is half the amplitude of the swing.

Let us take the case of a pendulum beating half seconds —that is, making a single swing in that time, its length L in feet will be—

$$\mathrm{L} = \left(\frac{\cdot 5 \text{ second}}{\cdot 5535}\right)2 = \cdot 8159 \text{ foot}$$

The maximum velocity will be, for a swing of six inches,—

$$v \text{ ft.} = \frac{\cdot 25 \text{ ft.} \times 2 \times 3 \cdot 1416}{1 \text{ sec.}} = 1 \cdot 5708 \text{ feet per second.}$$

The versed sine D E is the height which the bob falls each half excursion.

$$h = \cdot 8159 \text{ ft.} - \sqrt{\cdot 8159^2 - \cdot 25^2} = \cdot 0386 \text{ foot.}$$

Now, if our reasoning has been correct, we shall find that the potential energy of the bob equals its kinetic. Suppose the bob to weigh 1 lb. the potential energy, in the positions A or B $= \cdot 0386$ ft. $\times$ 1 lb. $= \cdot 0386$ foot-pound. The kinetic energy in the position E where the velocity is a maximum, and $= 1 \cdot 5708$ ft. per second.

$$\text{Kinetic energy} = \frac{1 \cdot 5708^2 \times 1 \text{ lb.}}{64 \cdot 4} = \cdot 0383.$$

The two results are practically identical.

The velocity with which a pendulum bob moves along its arc is not uniformly accelerated, because the tangential resultant of its weight, which impels it, is not constant, but varies as the sine of the angle a. It is greatest when the bob starts into motion, and vanishes when it reaches its lowest point. For moderate swings the time in which a pendulum completes its excursion is very nearly constant for all amplitudes of vibration.

In watches, the pendulum is replaced by a wheel attached to one end of a spiral spring, the other end of the spring being fastened to the framing which supports the mechanism. When the wheel is turned a short distance, the spring is either wound up or unwound, and by that means brought into a state of tension, and then, being set free, the spring restores the wheel to its original position, and in doing so converts the potential energy imparted by the forcible compression or extension of the spring into kinetic energy, and this expends itself in carrying the wheel as much past the neutral point as it had been moved in the opposite direction at starting. This oscillating motion would also continue for ever, were it not for the imperfect elasticity of the spring, the resistance of the air, and the friction of the journals; and, as in the case of the clock, these resistances have to be overcome by an escapement actuated by a wound-up spring, which gives the wheel a little push at each oscillation.

Vibrations may be propagated in many ways. Any elastic material may be set into longitudinal vibration. A wire stretched between two fixed points, if rubbed longitudinally, will be set into vibration. The action is of this nature. A portion of the wire rubbed is stretched a little more than the rest by the pull of friction; when the elasticity of the wire overcomes this pull, a portion of

wire springs back, and, being elastic, returns beyond the neutral position as far as it was dragged from it. The motion is analogous to that which we see in the pendulum and balance; the elasticity of the material is the moving force. In obedience to the third law of motion, no part of a continuous bar can spring backwards and forwards without the neighbouring sections participating in the movement, and so the oscillation travels along the bar according to well established laws; and because the wave of oscillation causes alternate compression and extension in the bar, it must also cause corresponding changes in its cross section, for most solid substances do not change sensibly in volume under stress—the bar will be reduced in diameter where extended, and increased where compressed. It is probably to this change of diameter, slight though it be, that we are indebted to the beneficial results of "jarring" —anything which we wish to get out of a hole into which it has been very tightly fitted. The sudden alternation from compression to tension in highly elastic and brittle bodies, such as glass, is so intense that they may be fractured into thin slices through being brought into longitudinal vibration by vigorous rubbing.

The mode by which longitudinal vibrations are established and propagated may be very distinctly seen by fastening to some support one end of about a yard of india-rubber pipe, and holding it out horizontally, but without stretching it much, with the hand; then, if the end near the hand be well wetted, and the fingers of the other hand rubbed lightly over it, the pulsations will be distinctly felt as they are formed by the alternate catching and releasing of the pipe by the fingers. The vibrations will be propagated along the pipe to the opposite end, and will become apparent as transverse vibrations

which result from the sudden alterations of length, due to the pulsations, jerking the pipe up and down.

Fig. 14 represents an apparatus consisting of a brass tube fastened securely by its middle to a stout board. Opposite one end is hung a small glass ball. When the rod is rubbed with the gloved hand, powdered with a little rosin, a musical note is heard, and at the same time the ball is repelled with violence from the end of the rod. The note is between F sharp and G, corresponding to about 1,400 pulsations per second; therefore, although the excursion of each portion of the rod is but small, the

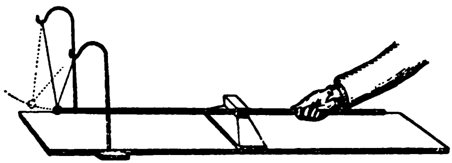


FIG. 14.

velocity is very great, and hence the sharpness of the blow delivered to the ball.

All solid substances may be brought into transverse vibrations. Familiar illustrations of this are tuning-forks, the sounding-boards of musical instruments, and stretched strings. When these motions are sufficiently pronounced, they can be seen by the naked eye; but when very rapid and of small amplitude, they can be made to register themselves, so as to become visible, by mechanical means.

Waves are propagated through fluids and gases, such as water and air, much in the same way as along a rigid bar, that is to say, by alternate compression and extension; but the lines of compression and rarefaction extend all round the point from which the impulse is given, spheres of

compression being surrounded by spheres of rarefaction, and consequently the impulse travels outwards in every direction; and as the energy of motion is imparted to constantly increasing masses, so the amount of motion is decreased, and the waves become more and more feeble as they recede from the point whence they started. Waves on the surface of a liquid are produced by a similar oscillation of the particles of the liquid, that is to say, each particle describes a curve of elliptical form, the plane being in the direction of motion of the waves, the long axis in deep liquid being horizontal. The moving force is

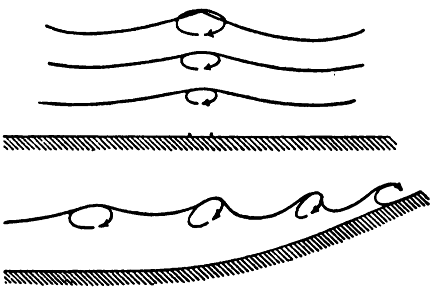


FIG. 15.

usually one acting on the surface, generally the action of the wind; the disturbance is propagated deeper and deeper, the energy of motion acquired at the surface is communicated to greater masses, and hence the motion becomes more feeble, the elliptic paths of the particles become flatter, and at last vanish altogether. In moderate depths, when the bottom is reached, there remains a simple to and fro movement. As water, for example, shoals towards the shore, the lower part of the orbits of the particles is retarded; hence the long axes of the ellipses become sloping, they approach more and more to the

vertical, and at last the continuity of the ellipses is destroyed, and the wave breaks in a crest of foam on the beach. The action of the wind in creating waves is analogous to that of friction in producing pulsation in a solid rod, the friction of the air against the water which it slips over, tends to move the particles along and heap them up; this heaping goes on till the weight is more than the friction of the air can support, the mass of water falls, and, like the pendulum, falls as much below the mean level as it was raised above it. The elliptic motion is due to a combination of the vertical motion produced by gravity, and the horizontal motion due to the wind.

Wave motion, like all other oscillating movements, once started would go on for ever, were it not that the resistance of the air and friction of the particles of water among themselves tend gradually to bring the particles to rest. The movements which have been described may be plainly seen from any pier in deep water. Looking down on the waves, and observing some floating object, it will be seen to move a little backwards and forwards as well as up and down, while in shoal water the weeds growing on the bottom are seen to wave to and fro only.

If the surface of the sea be watched, it will be noticed that an infinite series of waves exist at the same time, and are being propagated in various directions. This is in accordance with the second law of motion, and we should expect, consequently, that if the motions of two waves happen to be in the same direction, that the motion of the water would be augmented; and, on the contrary, if the motions happened to be in opposite directions it would be reduced, while, in the intermediate stages, there would be a resultant motion depending upon the magnitude and direction of the other two. This effect is known by the

name of "interference" of waves, and may best be studied on the surface of calm water, in which waves may be generated at pleasure. In a calm sea, the long smooth rollers, intersected in various ways by minor waves, may also be watched with much profit. It is not alone in water that this interference takes place, but in all cases of vibration, whether in solids, liquids, or gases, the main vibrations are accompanied by minor ones. In musical instruments these minor vibrations are called harmonics or overtones, and to them is due the quality, tint, or *timbre* of the note. The difference in richness of the pure fundamental note and the one accompanied by its overtones, is much like the difference between the sea on a very calm day and the sea when a breeze is sweeping over it. In the former case you see only the long, sleepy, oily-looking swell of previous disturbance; in the latter, the same swell decorated and rendered brilliant by innumerable systems of wavelets superimposed on the majestic rollers of the swell, and on each other. In the same way interference of pulses in the air are recognised by the dullest ear as "beats," that is to say, periods of comparative silence caused by the neutralising coincidences of regions of compression and rarefaction in the sound wave.

A very beautiful method of studying wave motion is by means of a shallow tank with a glass bottom through which the light of a lamp can be directed by means of an inclined mirror placed underneath. A screen of tracing-paper inclined over the tank receives the image of the waves with great clearness, and records faithfully the effects produced by generating waves at one or more points, by reflections from plane and curved surfaces, and by interference.

As a consequence of the second law of motion, all wave

motions are capable of being augmented by fresh impulses communicated synchronously, that is, timed so as to be always in the direction in which the particles are moving, or of being diminished and neutralised by the opposite course. The energy competent to produce wave motions is small compared to the apparent results. Thus, on the sea, the friction on the surface of the water of a brisk breeze, having a velocity of 30 feet per second, is but $\frac{1}{10}$th of an ounce per square foot, yet the constant and synchronous application of this slight force is capable of raising considerable waves. The power necessary to produce the volume of sound which emanates from a large organ is not more than that which one man working the bellows can easily supply, and yet the flood of sound fills a spacious building, and is even competent to affect it with a perceptible tremor. The lightest touch of a wetted finger on the edge of a tumbler will set it vibrating with exceeding rapidity, emitting a shrill note, while the slight pressure of a feather will instantly damp the vibrations of a piano string.

The last kind of vibration which remains to be noticed is that of a mysterious substance which, for want of a better name, we call ether, which pervades all space and all bodies, whether solid, liquid or aëriform. It is this ether which links us to the planetary world, for it is the medium by which light and heat are communicated to the earth from the sun and the other heavenly bodies. It must be of extreme tenuity, because it offers no appreciable resistance to the motion of the planets, and, as I have just said, permeates all substances. It may be difficult at first to accept the statement that solids can thus be permeated, but we have reason to believe that, looked at with the mind's eye, the densest solid is no better than a very

porous piece of sponge. The evidence of the truth of this statement lies in the remarkable phenomena of the occlusion of gases in solids and liquids, that is to say, the power which solids and liquids possess of absorbing many times their own bulk of certain gases. Thus platinum, the densest of all substances, occludes as much as five times its own volume of hydrogen without change of bulk; the metal palladium as much as 643 times its own volume of carbonic oxide. It is, in fact, upon this property that the manufacture of steel from wrought iron by the cementation process depends. In that process bars of wrought iron are packed with substances rich in carbon into iron boxes, and closely cemented in them; they are then exposed to a red heat for many days, during which carbon slowly penetrates right into the heart of the bars. Again, platinum and iron are, at a red heat, permeated by gases to a remarkable extent, that is to say, gases pass right through them. Liquids, also, absorb many gases readily. Rain-water takes up $2\frac{1}{2}$ per cent. of its bulk of atmospheric air, and the principle on which the manufacture of aërated drinks depends is that water can, by pressure, be made to hold many times its bulk of carbonic-acid gas. At the atmospheric pressure water dissolves about its own volume of the gas; but as the pressure rises, and the gas is reduced in bulk, more gas is absorbed, and it is found that the weight of gas taken up is nearly in direct proportion to the pressure, a relation which the theory of the porosity of bodies would lead us to expect.

Our knowledge of molecular physics is still very limited; the subject is now occupying the attention of some of the most powerful minds of the age; it comes within the province of the chemist, the mathematician, and the physicist, and any theories put forth must satisfy

the claims of each. Speaking broadly, I may say that the elementary substances are composed of atoms or particles incapable of further subdivision, and these atoms have each a definite weight, and probably a common specific heat, that is to say, each atom requires the same quantity of heat to raise its temperature one degree. Compound bodies are composed of molecules which are formed, each, of a definite number and arrangement of the atoms of the elements of which they are composed. Of the structure of the atoms and molecules little or nothing is known, though many bold and ingenious conjectures have been made, but long years will probably elapse before any fully satisfactory theory can be established. The atoms of simple substances, and the molecules of compound bodies, are not in permanent contact with each other. In solids they are in a state of oscillation, the amount of which depends upon their temperature; this oscillation is analogous to that of a pendulum or watch balance, the forces acting on the particles being mutual attraction, and that force, which causes the movement, which we call heat. Molecular motion, like any other, may be communicated from one body to another, or propagated along the same body, in the manner illustrated by the experiment with the brass tube. A body in which the particles are oscillating more vigorously than in another body, if placed in contact with it, will gradually impart a portion of the motion of its own particles to those of the body it touches, and in consequence the motion of its own particles will be enfeebled, because the total kinetic energy of the two substances necessarily remains constant.

If a number of heavy balls be hung from the horizontal bar of a light frame, and if one of the balls be set swinging across the frame, the pull upon its string, due to the motion, sets the top bar of the frame moving synchron-

ously; this motion is imparted to the points of suspension of the other balls, and by that means they all gradually get into swing, and as their swing increases, that of the ball which originated it decreases. This illustrates how heat vibrations are communicated from one body to another, and how the former must necessarily cool in heating that with which it is in contact.

A vibrating string, if it has light substances showered down on it, sets them in motion, but in so doing, it has its own velocity reduced. A string vibrating between rigid supports will continue to sound longer than one attached to a sounding-board, because, in the latter case, much more motion is communicated to the air, the sound is much louder, and hence the motion of the string is more quickly damped. The same action takes place in the communication of heat from one body to another by conduction, or from the hotter portion of one body to a colder portion; the rise in temperature—that is, the increase in the amplitude of vibrations of the colder body—is accompanied by a fall in temperature of the hotter. When such increased motion is communicated, the particles make wider excursions, and generally cause the body to expand. At last a point is reached at which the bonds of cohesion have been so weakened by the separation of the particles, that they escape from the influence of the other particles they were associated with, and become free to slide over each other, the consequence of which is, that the solid substance becomes liquid. In both these states the violence of motion flings off, as it were, particles at the surface, in consequence of which most solid and liquid substances have a characteristic smell, and many of them, such as snow, ice, and sal ammoniac, evaporate with tolerable rapidity, even at very low temperatures. In the case of

liquids, the particles in the mass of the substance are in equilibrium, and move indifferently in any direction; but when a free surface is reached, the outward movement has to take place against the force of gravity so soon as any particle tends to rise above the level of the rest, and hence the tendency of liquids to assume a horizontal free surface. Yet from this surface particles are occasionally projected and escape into the air, assuming the form of vapour; and this escape, as might be expected, is more frequent the more rapid the motion of the particles is—that is to say, the hotter the liquid becomes. In gases, the motion of the particles is similar to that in liquids, but more energetic. They move with great velocity in all directions, striking against each other and against the sides of containing vessels, and rebounding according to the laws of impact of elastic substances, which have been briefly explained. It is the continued bombardment of the sides of the containing vessels by particles extremely minute, inconceivably numerous, and gifted with a stupendous energy, due to their high velocity, which produces the phenomena of pressure and temperature of gases. Were the molecules or atoms perfectly elastic, and were there no friction or resisting medium of any kind, there would be no loss of energy, and hence a gas completely enclosed in a non-conducting vessel would never change its temperature. There is, however, one source of apparent loss of energy, and that is that the innumerable collisions among the particles tend to set up very minute vibrations in the substance of the atoms and molecules themselves, and this action would produce the same effect as in the collision of elastic bodies, where it has already been shown that the internal vibrations rendered sensible to us in the form of sound are competent to bring the bodies to rest. In the case of gases, the internal

molecular vibrations set up would probably not have the character of sensible heat. All gases are supposed to contain the same number of elastic molecules in the same volume, under similar conditions, hence their specific gravities are proportioned to their atomic weights, and their physical properties are also very much alike—that is to say, they obey the same laws of variation of volume and pressure with respect to heat. The space passed through by a particle of gas without collision is termed the free path. There is a difference in the nature and properties of gases in the three following conditions:—When in contact with the liquids from which they have become disengaged; when completely separated from their liquids; and again when, at high temperatures, dissociation or a sub-division of the molecules takes place, so that when examining a gas, its condition requires to be defined. The evidence of the truth of the molecular theory of liquids and gases is, that they diffuse into each other—that is to say, two different liquids, or two different gases in contact with each other, will mix more or less rapidly, which proves that the particles are free to perform excursions of unlimited extent. This tendency is so powerful, that when liquids or gases are separated by porous substances, they will nevertheless mix with each other; and as the rate of transmission depends on the relative densities of the two bodies, the lighter substance will pass more quickly in one direction than the heavier one in the other, and by so doing produce unequal pressures against which, nevertheless, diffusion goes on. Thus hydrogen escaping from a vessel, through a porous partition, into the air, will leave a partial vacuum behind. A solution of red litmus separated from a solution of ammonia by a plug of wood about one quarter inch thick will mix gradually, both

E 2

liquids turning blue, thus demonstrating that a movement of molecules in both directions has taken place. Mathematical calculations based on these theories enable us to account for the laws relating to the pressure, temperature, and other properties of liquids and gases.

Although the heat and light-bearing ether is of the nature of a gas, or rather of an extremely elastic jelly, yet vibrations rendered evident as radiant light and heat do not take place in the direction in which the tangible effects seem to travel, but at right angles to them, like a wave travelling along a string, and these vibrations are extremely complex; they are made up, not only of vibrations of various wave lengths vibrating in the same plane, but of vibrations in planes at right angles and other angles to each other. The waves are of inconceivable minuteness and rapidity of motion, else they could not be expected to traverse solid substances. By means of a transparent triangular prism, rays of white light can be decomposed, that is to say, the effect of the form of the prism on a ray from a hot body is to separate the various complex vibrations into ones of definite wave lengths. The visible spectrum (Fig. 16) is bounded by red at one end and violet at the other, but beyond the red, invisible to human eyes, the heat rays spread out, and beyond the violet, equally invisible, the chemical rays. The length of a wave of the extreme red is 39,000 to one inch, and of the violet ray 64,631 to one inch. The velocity of light is 186,000 miles a second, hence the red waves strike the retina of the eye at the inconceivable rate of four hundred and sixty millions of millions of times in each second. The analogy between the comparatively coarse motions of sound and those of radiant light and heat are very remarkable, and have, in fact, been the means of leading up to the now

well-established undulatory theory. It is well-known that musical sounds extend beyond the compass of the human ear, and that ears are not all alike in respect of their powers of hearing extreme notes at either end of the scale; some people, for instance, cannot hear the cry of a bat. The same thing applies to light; we cannot perceive the excessively rapid vibrations beyond the extreme violet of the spectrum, or the comparatively slow movement of the red end, but we can damp the too rapid vibrations by letting the dark rays fall on certain substances, such as sulphate of quinine, and then we are made conscious of fluorescence—light shining out of darkness. Any idea

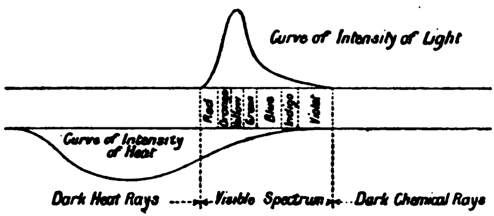


FIG. 16.

that there is a substantial difference between rays of heat, of light, or of chemical action must be banished from the mind. The difference is only one of wave length, and it is due to the structure of our organs of sense that only certain of the vibrations produce the sensation of light and others that of heat. In the case of the chemical rays, their superior energy, due to the velocity of motion, may be the cause of their power of decomposing certain substances.

A string made to vibrate, as has been already stated, vibrates in a complex manner, the fundamental note is accompanied by overtones and harmonics; by damping

the string in suitable places, the overtones may be extinguished and the fundamental note sounded alone. And so with light and heat. The rays may be sifted by being passed through certain media, such as water, and emerge shorn of the undulations causing the sensation of heat, or through coloured transparent substances and issue possessed only of the wave length of any colour we may like to select. Again, the vibrations in every conceivable plane may be reduced to vibrations in one plane only; this is termed polarisation; and as we have seen that sound waves interfere with each other, so do the waves of heat and light. The iridescent colours seen in soap bubbles, and in thin films generally, are caused by the interference of certain wave lengths reflected from the two sides of the film abolishing certain colours, and destroying the usual whiteness of the light by giving prominence to the complementary colours.

The diathermancy of substances, that is, their transparency to heat, is so intimately connected with our subject, that some time must be devoted to it. It is a matter of every-day observation that substances are endowed with varied degrees of transparency, that is to say, that the undulations corresponding to visible rays make their way among the particles of some bodies, and are arrested in whole or in part by others. For example: glass, water, and air, allow the luminous rays to pass with only slightly altered intensity. A certain diminution of energy, indeed, depending upon the thickness of the medium, takes place, as might be expected, from the vibrations having to pass through a crowd of vibrating particles of the substance through which the light is transmitted. If a monochord, —Fig. 17—be threaded through a tin cylinder fitted with several internal ledges or shelves, and if the cylinder be

partially filled with fine sawdust, and turned, the sawdust will be showered down upon the string. When a note is sounded, while the cylinder is at rest, its prolonged cadence gradually dies out; but if, at the same time, the cylinder be turned, the particles of sawdust, as they fall on the string, are set in motion and the energy so imparted is deducted from the string, consequently the sound is quickly extinguished. This is analogous to the effect of radiant light and heat passing through substances the particles of which are capable of responding to the vibration of the ether, and themselves, consequently, becoming hot at the expense of the radiant energy.

The experiment with the swinging balls will serve also

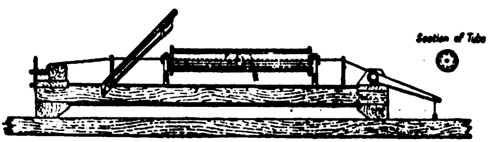


Fig. 17.

to illustrate this point. When the balls are arranged so as to have the same period of oscillation, they all get into swing upon one of their number being set going. This represents the cases of an adiathermanous body which will not transmit radiant heat, and, therefore, gets hot itself. But if one or two of the strings be shortened, and so give the corresponding balls a period of vibration which does not synchronise with that of the swinging ball, they will remain quite unaffected; that is the case of a diathermanous substance which does not get hot itself, but allows the heat rays to pass through.

In the case of light, some substances only affect certain wave lengths and arrest their movement altogether,

we then have coloured light such as is produced by coloured glass, liquids and gases. A very large number of substances, when they are of appreciable thickness, will not permit the waves to pass at all, and then we have opaque bodies.

The same rules apply to the heat waves, and what we know of light will lead us to expect that the heat waves will be more interfered with by some bodies than others, and that transparency to light need not be accompanied by transparency to heat, and so we find that transparent rock salt is also diathermanous, whereas glass and water very greatly damp the longer heat waves. Gases also vary considerably in their effect on radiant heat. Atmospheric air, oxygen, hydrogen, and nitrogen scarcely produce any effect on heat waves, whereas olefiant gas and ammonia interfere with them to a very considerable extent.

The remarkable adiathermancy of water is taken advantage of by diamond cutters and engravers, to concentrate a powerful pencil of light on their work without the accompanying heat. Instead of using glass lenses, they use globular vessels filled with water, which act as water lenses, concentrating the light while they completely cut off the heat. Firescreens have been contrived, formed by a sheet of water arranged to fall in front of the fire from a slit under the mantlepiece into a trough concealed by the fender.

Our knowledge of the diathermancy of the metals and other substances used in the arts is very limited. Melloni, from whose experiments most of our information is derived, operated chiefly on substances more common in the laboratory than in every-day life; but we may safely say that all substances are more or less diathermanous, and

that the thinner the substances are, the less the heat waves are interfered with.

We are now in a condition to explain many of the phenomena connected with heat.

First, we will take specific heat. It is a matter patent to our senses that there is a great difference in the physical properties of bodies. They differ in specific weight, in strength, in elasticity, in colour, in hardness, and in many other more subtle points, hence we might expect that the atoms or molecules would not be set vibrating with equal facility. We have seen that a force of 10 lbs. acting on a weight of 10 lbs. will produce a definite velocity in a second of time, but if the force of 10 lbs. act on a weight of 20 lbs., the velocity will be reduced to half; and so it is found that a pound of water, the molecules of which are endowed with energy competent to produce the sensation of 100° Fahr. of heat, if mixed with a pound of water, the molecules of which are moving with less energy, and producing the sensation of 50°, the former will lose a portion of their motion, while the cold water will gain; the momentum of the two pounds of molecules vibrating at a common velocity will remain the same as the sum of momenta of the respective pounds before mixture—in other words, we shall have two pounds of water at 75°. But when the substances mixed together are different, the change of velocity of motion is not so simply arrived at, because not only are the weights of the particles of the two substances different, but the forces which unite them, and which oppose the change of motion, are also different. Thus if 1 lb. of mercury at 100° be mixed with 1 lb. of water at 50°, the result will be a mixture at 51·61° only, the reason being that the energy of the vibrations in mercury is only about 3⅓ per cent. of that of the molecules of water. This

relation of the energy of vibrations of various substances to water is called the specific heat of the substance. It has been determined with great care for most bodies, and always takes the form of a decimal fraction, water being unity, for it so happens that water requires more heat to raise it a given number of degrees than any other substance. The specific heat of mercury is ·0333, that of iron ·1138, that of alcohol ·615, that of air, ·169, at constant volume. Specific heat in simple substances and in compound bodies of similar atomic composition, is found to vary inversely as the atomic weight—that is to say, the product of the atomic weight into the specific heat is very nearly a constant quantity in the elements and compound bodies of the same order, the said product varying in value with each order.

It has been stated that water has been constituted the standard to which specific heats are referred, it is now necessary to explain that the quantity of heat or energy of molecular vibrations which raises one pound of water one degree of Fahrenheit is called the British unit of heat, and because it is a fact that energy is indestructible, so heat, being a form of energy, is also indestructible, it cannot disappear or be lost; hence all calculations connected with heat are based upon the supposition that whatever changes of temperature take place, the total amount of heat units involved will remain unaltered in value, though, perhaps, greatly changed in form. By way of illustration, we will take a convenient method of measuring very high temperatures. It consists in heating a ball of some refractory metal to the same temperature as that which it is desired to measure, and then, with proper precautions against loss of heat, plunging the ball into water. In order to use this apparatus it is only necessary to know

the specific heat of the material of which the ball is composed, its weight, the weight of water into which the ball is plunged, and the increase of temperature in the water. Supposing that a ball of platinum, weighing one pound, had been heated white hot in a furnace, and then plunged into one pound of water at 50°, and that after a time the water had risen to 112°, a simple calculation will show that the ball must have been at a temperature of 2025·3°. The specific heat of platinum is ·0324. Let us now make a debtor and creditor account. Before the ball was quenched we had the following number of heat units:—

In the platinum ball,	2025·3° × ·0324 × 1 lb. =	65·62
In the water	50° × 1 lb. =	50
	Total heat units..	115·62

After the ball was quenched, and had got to the same temperature as the water, we had—

In the water 112° × 1 lb.	= 112·	units.
In the ball 112° × ·0324 × 1 lb. =	3·62	
	115·62	

The account balances, and it is on that expectation that the formula is based by which the temperature of the ball is calculated.

W = weight of water at temp. t being also that of the air.
W′ = weight of ball.
t' = temperature of ball before quenching.
t'' = temperature of water and ball after quenching.
S = specific heat of ball.

Units of heat in the ball = $W' S \times (t'-t)$.
Units of heat after mixture $= W \times (t''-t) + W' S \times (t''-t)$.

These two quantities are equal to each other, hence it

is easy to work out that t', the temperature of the ball when plunged into the water, will be—

$$t' = \frac{(t''-t)\,(W + W'\,S)}{W'\,S} + t$$

It has already been explained how, when the energy of molecular vibration is increased in a solid, the molecules become emancipated from the rigid thraldom in which they were bound, and the solid becomes a liquid. If still more energy be communicated, the liquid becomes a gas.

Now, in the case of accelerated motion, we have seen that as long as the accelerating force acted, the motion of the body acted on continued to increase; but as soon as the accelerating force was diverted or ceased to act, the motion remained uniform, the effect produced by the force remains, according to the first law of motion, though the force has disappeared. So it is with heat motion imparted to a body. So long as the body heated retains its normal form and properties, we can observe the increase of temperature corresponding to an increase of molecular energy; but as soon as destruction of form begins to take place, the increase of heat no longer becomes sensible, the energy of the force is diverted to breaking up the structure of the body, and to keeping its molecules apart and free to slide over each other. When this has been completely accomplished, and not till then, additional energy imparted again produces accelerated motion, and the liquid gets hotter and hotter, till at last a second boundary is reached, a second destruction of form takes place, and again the rise of temperature ceases till the whole liquid is transformed into a gas; after which acceleration can again take place and the gas become further heated, whereby the energy of its molecules, already very

high, is still further increased. The heat which apparently disappears during liquefaction and vaporisation is said to be latent, which means no more than that heat, like many persons, cannot do two things at the same time. The work of pulling to pieces the structure of a solid or liquid cannot go on if the mercury in the bulb of a thermometer has to be expanded and made to rise at the same time.

If we wish to restore the substances to their original states, we must arrange matters so that the energy which is keeping the molecules of a body apart shall be diverted to heating some other body, in other words, we must cool the vapour to make it return to the liquid form, and cool the liquid to make it become solid again.

Degrees of temperature have frequently been mentioned, and it is hardly necessary to explain that the ordinary mercurial thermometer is a contrivance by which the expansion of mercury in a narrow glass tube enables us to measure changes of heat which affect our senses. The two fixed points in a thermometer scale are the melting point of ice and the boiling point of water, the space between having been divided, in England, into 180°. Fahrenheit, however, to whom we owe our thermometer scale, had an idea that there was a zero point, a point beyond which temperature could not fall, and he fixed it at 32° below the freezing point of water. Fahrenheit was right in his idea, but quite wrong in the zero point he fixed. We have now better grounds upon which to arrive at what is termed the absolute zero of temperature. A perfect gas is found, by experiment, to expand or contract regularly in direct proportion to the alteration of temperature, and the rate of expansion is such that a volume of 1 at the freezing point becomes a volume of 1·3665 at the

boiling point, a range of 180°, so that the volume has increased by $\frac{1}{492}$ part for each degree of rise of temperature. On cooling the gas, it is found to contract at the same rate, so that supposing it could be cooled 492° below the freezing point, the gas would occupy no volume at all. It is this point which is called the absolute zero of

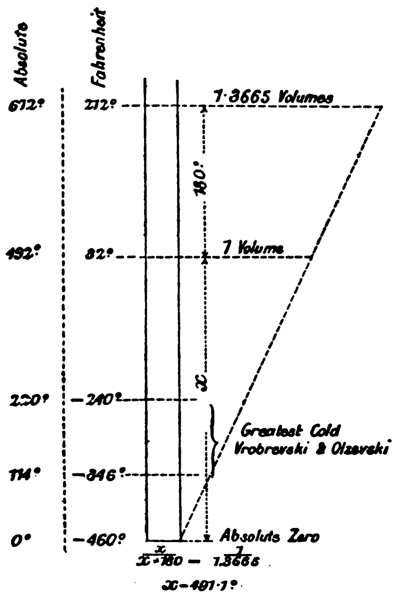


Fig. 18.

temperature; it is 492° below the freezing point, or —460° on Fahrenheit scale. To convert our ordinary degrees into absolute temperature, therefore, we have only to add 460°.

Fig. 18 represents the above calculation graphically The vertical parallelogram represents a tube, closed at the bottom, containing, up to the point 32°, one volume of air

If this be heated to 212° the volume becomes 1·3665. Drawing horizontal lines from 32° and 212° to represent these values, connecting their ends by a diagonal and producing it till it cuts the tube at x° below 32°, we have, from the property of similar triangles, the following proportions, $\frac{x}{180° + x} = \frac{1 \text{ volume}}{1 \cdot 3665 \text{ volume}}$, whence $x = 491{\cdot}7°$.

It may be asked whether it be possible that gas, deprived of all sensible heat, will cease to cccupy space? The present state of our knowledge does not enable us to answer the question. The lowest temperature reached up to the present time has been attained by the Russian chemists, Wrobrevski and Olsevski, and is 114° on the absolute scale. The absolute zero of temperature can be arrived at also by other means, which it is beyond the scope of this work to explain.

The thermometer scale now generally accepted in the scientific world is the "Centigrade," in which the 180° F. from the freezing to the boiling point is divided into 100 parts, hence absolute zero on the Centigrade scale is $= \frac{x}{100° + x} = \frac{1}{1 \cdot 3665}$, $x = -273°$ C.

The unit of heat in the metric system is called a "calorie," and is the quantity of heat necessary to raise one kilogramme (2·205 lbs.) of water 1° C. The calorie is nearly four times larger than the British heat unit. To convert the latter into the former it must be divided by 3·969.

CHAPTER III.

We have now to consider the properties of gases and vapours. It has already been explained that aëriform substances exist in different conditions; first, near the temperatures and pressures at which they separate from their liquids, when the temperature of the gas is the same as that of the liquid from which it is formed, when the energy of motion of some of the molecules in the liquid is constantly being raised to a pitch which causes them, under favourable conditions of position and direction of motion, to leave the liquid and escape into the free space above. Suppose the bob of a pendulum could be set free at the moment when it reaches its lowest point or point of maximum kinetic energy, the bob would continue to move at a uniform velocity for ever, and if perfectly elastic, and surrounded by equally elastic walls and other particles, would continue to strike and rebound from them in all directions without any loss of energy. An ordinary pendulum continues to swing to and fro; the energy of both is the same, only it is all kinetic in the free bob and perpetually changing from kinetic to potential in the pendulum; and so it is when a solid passes into a liquid, the average energy of the molecules is the same, but in the solid the excursions of the particles are limited by the force of cohesion, while in the liquid there is no such limit; therefore, as the temperature depends on the energy

of motion, it must be the same in the solid and liquid while the change is taking place. In the case of liquids and gases, the motion of the molecules is similar in character, but the average motion in liquids is less than in gases, though it often happens that some molecules of a liquid attain a higher velocity than the average motion of the molecules of a gas, and in such cases they may, under favourable circumstances of position, detach themselves from the liquid and become parts of the gas, and, on the other hand, some of the molecules of a gas may have less motion than the average of those of the liquid, and would, therefore, on coming in contact with it, revert to the fluid condition.

If the molecules of the vapours are brought nearer together, when in this critical state, by compression, some of them have their excursions shortened till they again come within the power of attraction, and the vapour becomes in part a liquid, so that the pressure cannot be sensibly raised without a preliminary increase of temperature. This critical point varies greatly in different substances. Oxygen, for example, at 252° Fahr. below the freezing point, or at 240° Fahr. on the absolute scale, liquefies under a pressure of 320 atmospheres or 2·1 tons per square inch, while hydrogen, at the same temperature, requires more than double the pressure, or 650 atmospheres, corresponding to 4·3 tons per square inch. Carbonic acid gas liquefies at a temperature of 88° Fahr. under a pressure of 75 atmospheres. The substances seem to be in a condition between the liquid and the gaseous, the molecules being so packed together in proportion to their energy of motion, that some are under the influence of cohesion and others darting about unrestrained.

The volume, pressure, and temperature of gases, far

removed from their points of condensation, have certain relations to each other defined by the laws of Boyle or Mariotte, and Charles or Gay-Lussac.

According to Boyle's law, the product of the volume (v) and pressure (p) of a gas is always a constant quantity at the same temperature: that is to say, if you reduce a given volume of gas to half its bulk by external pressure, and arrange so that the temperature shall not change, then the pressure will be doubled. This relation is thus expressed $p\,v = p_1\,v_1$. According to the law of Charles, the pressure of a gas confined in a fixed space, and the volume of a gas free to expand, will vary as the absolute temperature,

$$\frac{p\,v}{p_1 v_1} = \frac{t}{t_1}$$

Suppose 1 cubic foot of gas at 50° or 510° absolute, what will be the volume at 212°, or 672° absolute, if there be no change of pressure? The answer is

$$\frac{1 \text{ c. ft.} \times 672^\circ}{510^\circ} = 1 \cdot 31 \text{ cubic feet.}$$

Suppose 1 cubic foot of air at 510° absolute temperature and 100 lbs. absolute pressure, that is, pressure measured from perfect vacuum, compressed to half its volume and heated to 212° or 672° absolute, what will be the pressure?

$$\frac{100 \text{ lbs.} \times 1 \text{ c. ft.}}{p_1 \times \cdot 5 \text{ c. ft.}} = \frac{510^\circ}{672^\circ}$$

$$\therefore p_1 = \frac{100 \text{ lbs.} \times 1 \times 672}{510^\circ \times \cdot 5} = 263 \cdot 5 \text{ lbs.}$$

If $v\ p\ t$ represent volume absolute pressure and absolute temperature, and $v_1 p_1 t_1$ the volume pressure and temperature of the same weight of gas under other circumstances,

$$\text{Boyle law gives } v\,p = v_1\,p_1$$

$$v_1 = \frac{v\,p}{p_1} \text{ and } p_1 = \frac{v\,p}{v_1}$$

from which the volume and pressures at constant temperature may be ascertained; and because both the volume and the pressure vary as the absolute temperature, then, when there is a change of temperature,

$$v_1 = \frac{v\,p\,t_1}{p_1\,t} \text{ and } p_1 = \frac{v\,p\,t_1}{v_1\,t}$$

The properties of a gas may be graphically exhibited by means of a curve.

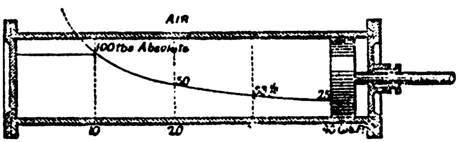


FIG. 19.

Suppose a cylinder, Fig. 19, fitted with an air-tight piston, and that 10 cubic feet of air at 100 lbs. absolute pressure, that is, pressure measured from a perfect vacuum, were imprisoned between it and the end of the cylinder. If the piston were drawn out, equal distances would represent equal volumes, so that the length of stroke would be proportional to the volumes assumed by the gas. On the diameter of the cylinder set off a length proportional to 100 lbs. pressure, and let the temperature be kept constant at, say 60°, then according to Boyle's law, when the volume had doubled, or increased to 20 cubic feet, the pressure would be halved, or only 50 lbs. When the volume increased to 30 cubic feet, the pressure would be only $33\frac{1}{3}$ lbs., and so on. It will be noticed from the

diagram that the curve of pressures keeps getting nearer and nearer to the zero or base line, but inasmuch as we can never, by division, reduce anything to nothing, it follows that any amount of expansion can never annihilate the pressure altogether, though it may reduce it to less than anything we can name. The curve we have traced is called an isothermal line, because the gas throughout is assumed to be at the same temperature. The action I have described is reversible, that is to say, when the motion of the piston is reversed, the gas will be compressed, and the pressure will form ordinates to the same curve, if there be no change of temperature.

But if the gas operated on be near its point of lique-

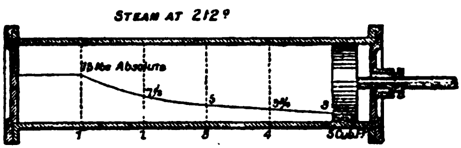


FIG. 20.

faction, matters are not so simple. Such a gas we have in steam. Let us suppose a cylinder 5 feet long, (Fig. 20,) filled with steam at 3 lbs. absolute pressure, and 212° temperature. If the piston were pushed in, the pressure would rise, nearly, according to the isothermal curve until a pressure of 14·7 lbs. or one atmosphere was reached, and then we should attain a pressure and temperature at which water may exist either as a liquid or a gas. The slightest increase of pressure causes the steam to condense, and therefore the isothermal line will cease to be a curve, but will be a line parallel to the base, indicating that there will be no further rise of pressure till all the steam is condensed. When that happens, there will be less than a

7,000th part of the original bulk of steam reduced to water at 212° temperature, and practically incompressible. The reverse action would take place supposing the minute volume of water were kept at 212° while the piston was drawn slowly out, the water would boil away and would all become steam by the time the first foot had been passed over, and then the pressure would diminish according to the law of Boyle.

It is not easy, in treating of the conversion of heat into work, to arrange the subject so as to refrain from taking for granted that which requires to be explained; and in order to avoid committing such an offence, we must, for a time, leave the behaviour of gases under varying pressures and temperatures, and direct our attention to the mechanical equivalent of heat. Less than ninety years ago, it was an inexplicable puzzle whence came the heat developed, apparently without limit, and without change in the properties of matter, in certain mechanical operations Count Rumford noticed the circumstance in the boring of cannon, and in 1798 laid before the Royal Society a description of the famous experiment from which he deduced that heat must be motion of some kind, and even made an approximation of its mechanical equivalent. Sir Humphry Davy succeeded in melting ice in an atmosphere at 29° by rubbing two slabs over each other, producing water at a temperature of 35°; and he announced the important proposition, that "the immediate cause of the phenomenon of heat is motion, and the laws of its communication are precisely the same as the laws of the communication of motion." Our more extended knowledge enables us to confirm the views expressed by Davy.

About thirty-five years ago Joule determined, by direct experiment, the mechanical equivalent of heat, and it is

now accepted as 772 foot-pounds, which means that the energy represented by the fall of 772 lbs. one foot is the same as that necessary to change the temperature of one pound of water one degree Fahrenheit. Joule's equivalent, as it is called, is known in mechanics by the letter J. According to the metric system a calorie is equivalent to 192 kilogrammetres, and a foot-pound to 0·1383 kilogrammetres.

We are now enabled to enunciate the first law of thermodynamics, which is, that "heat and mechanical energy are mutually convertible, and heat requires for its production, or produces by its disappearance, mechanical energy in the proportion of 772 foot-pounds for each unit of heat." It seems strange that, although instances of the conversion of heat into work and the opposite are so common, the relation between the two forms of energy was not earlier suspected. The heat produced by friction, by hammering, by the sudden stoppage of bullets, were phenomena familiar to all; the constant application of heat to produce power in heat-engines, though not so obvious, is an operation which might have led inquiring minds to suspect that the source of power was not the steam, but the heat developed by the fuel.

The establishment of the dynamic theory of heat, and the discovery of its exact mechanical equivalent, have enabled clear and definite explanations to be given to certain phenomena which before could only be recorded as facts; for example, the changes of temperature in the expansion and compression of gases. It was known that the specific heat of air, when the volume remained constant but the pressure was allowed to vary, was ·169, whereas the specific heat of the same air, when the volume was allowed to increase and the pressure to remain constant,

was ·238, that is to say, greater in the proportion of 1 to 1·408. Air under pressure, when allowed to escape into the atmosphere, is greatly chilled, whereas air might be expanded under the bell glass of an air-pump without any loss of sensible heat. The explanation is now easy. In warming air at constant volume there is no external work done, there is no enlargement of the space containing the perfectly elastic molecules, their energy of motion is increased, the velocity with which they strike the sides of the containing vessel and collide against each other is increased; but as the sides do not move, their energy performs no external work, but is rendered sensible in the potential form of pressure. A rise of 1° is obtained by the communication to each pound of air of ·169 heat unit. But when the sides of the containing vessel are moveable and the contained gas is heated, the molecules striking the sides with increased energy cause them to yield against the pressure of the atmosphere or other resistance, motion takes place, and work is done proportional to the pressure multiplied by the space passed through. The heat necessary to raise the sensible temperature of the gas 1° is increased by the equivalent of work done, and hence it is found that 1lb. of air under such circumstances requires ·238 unit of heat to raise its temperature 1°. We can work this out a little more in detail. A pound of air at the freezing point, or 492° absolute, measures 12·387 cubic feet. If we double the temperature without altering the volume, we shall raise the absolute pressure to two atmospheres, or 29·4 lbs. per square inch, and consume in so doing $1\text{lb} \times 492° \times \cdot169 = 83{\cdot}150$ heat units. If, however, we allow the air to expand while being heated, causing it to displace or lift the atmosphere, keeping the pressure constant to 14·7 lbs. per square inch, or 2117 lbs. per square foot,

we shall double the volume and displace 12·387 cubic feet of air, and the work done will be 12·387 cubic feet × 2,117 lbs. = 26,222 foot-pounds. Dividing this by Joule's equivalent, we get 33·966 units of heat absorbed in performing the work, and, therefore, 1 lb. of air will require 83·15" + 33·966" = 117·116" to double its temperature at constant pressure, and the ratio of the two operations will be—

$$\frac{117 \cdot 116''}{83 \cdot 15''} = 1 \cdot 408.$$

This ratio of the specific heat of air at constant volume to that at constant pressure is, therefore, 1 to 1·408, and is generally represented by the Greek letter γ, the value of which depends upon the nature of the gas. For steam considered as a perfect gas the ratio is $\frac{\cdot 37}{\cdot 48} = 1 \cdot 3$.

If air at a given pressure and temperature be allowed to expand while doing work, and if matters are so arranged that heat can neither escape or be communicated, the pressure will not follow the law of Boyle, but will be defined by what has been termed an adiabatic curve, or a curve which represents the pressure corresponding to any alteration of volume, on the supposition that heat neither enters nor leaves the gas, and that external work is being done as the gas expands.

The equation to the isothermal curve, as already stated, is $p_1 = p\frac{v}{v_1}$ while the equation to the adiabatic curve for air is $p_1 = p\left(\frac{v}{v_1}\right)^{1.408}$ that is to say, the pressure varies, not inversely as the ratio of the volume, but as that ratio raised to the power of γ which we have seen is, for air, 1·408.

In the diagram (Fig. 21) are drawn the isothermal and the adiabatic lines for 10 cubic feet of air at 75 lbs. absolute pressure and 300° temperature, that is, 760° absolute, expanded to 250 cubic feet. The two curves approach

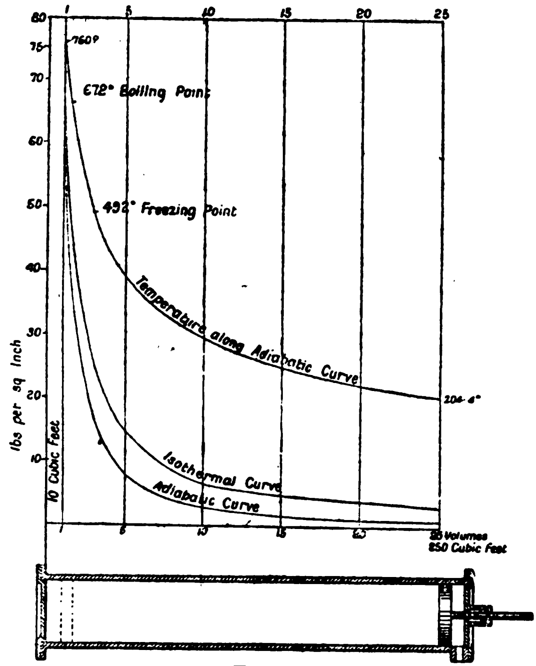


FIG. 21.

each other, and the base line; but for the reason already stated they can never touch it.

The volume of a gas varies as its absolute temperature $v_1 = \frac{v\,t_1}{t}$, and conversely the temperature varies as the volume $t_1 = t\frac{v_1}{v}$, but in the adiabatic curve, the temperature

falls as the gas expands, doing work, and may be calculated by the equation $t_1 = t\left(\frac{v}{v_1}\right)^{\gamma-1}$ or for air $= t\left(\frac{v}{v_1}\right)^{.408}$ that is, not inversely as the volume, but as that ratio raised to the power of $\gamma - 1$ or $\cdot 408$, which is not far from the square root. On the diagram is also traced the curve of temperature which the air will assume while expanding along the adiabatic curve. You will see that the curve of temperatures also tends to meet the two pressure curves. The areas of the spaces in the diagram between the pressure curves and the base line represent the external work done during expansion.

For the isothermal curve, which is a hyperbola, the equation for the work done is—

$$W = pv \log._{e} \frac{v_1}{v}.$$

The work done along the adiabatic curve is found by the equation—

$$W = \frac{p_1 v_1}{\gamma - 1}\left\{1 - \left(\frac{v_1}{v}\right)^{\gamma - 1}\right\}$$

$$W = \frac{p_1 v_1}{\cdot 408}\left\{1 - \left(\frac{v_1}{v}\right)^{\cdot 408}\right\}$$

The important principles we have been examining will become more tangible to the mind if numerical examples are taken: we proceed, therefore, to calculate the work done by the two conditions in the diagram. First expanding along the adiabatic line, so that the air pressure at the end of the stroke will be a little above that of the atmosphere, in order that it may be exhausted into it, we find that an expansion of three times brings the pressure down to 15·97 lbs., or 1·27 lbs. above the atmosphere, and the

temperature will fall from 760° to 485·4°, that is 7° below the freezing point, a fall of 274·6°. The weight of 10 cubic feet of air at 760° and 75 lbs. pressure is 2·6638 lbs.

The work done.

$$=\frac{75 \text{ lbs.} \times 144 \text{ s. in.} \times 10 \text{ c. ft.}}{\cdot 408}\left\{1-\left(\tfrac{1}{3}\right)^{\cdot 408}\right\}=95{,}638 \text{ foot-pounds.}$$

The number of units of heat which have disappeared is $= 2\cdot6638 \text{ lbs.} \times 274\cdot6° \times \cdot169 = 123\cdot6$ units, and the corresponding foot-pounds $= 123\cdot6 \times 772 = 95{,}436$ foot-pounds, very nearly the same as determined by the previous method. This shows that the work done depends upon the fall of temperature only, and not in any manner on the pressure or volume of the working substance, or its nature. In calculating the work from the change of temperature, the weight of the air in action must be ascertained, and to do that we must reduce it to the standard temperature of 492°, and pressure of 14·7 lbs., at which a cubic foot weighs 0·080728 lb.

The calculation then stands thus—

$$W=\frac{10 \text{ c. ft.} \times 75 \text{ lbs.}}{14\cdot7} \times \frac{492°}{760°} \times 0\cdot080728 \text{ lb.} \times 274\cdot6° \times \cdot169 \times 772 = 95{,}436 \text{ foot-pounds.}$$

It should be noticed in this sum, that 274·6° is the difference between the higher and the lower temperatures between which the air is working, and 760° is the higher temperature of the air, so that the work done is in proportion to the difference of temperature divided by the higher temperature; or if T be the higher and t the lower temperature, then the available work is proportional $\frac{T-t}{T}$,

which is a fundamental principle of the conversion of heat into work.

Counting from absolute zero, the total heat of 10 cubic feet of air weighing $2 \cdot 6638$ lbs. is $2 \cdot 6638 \times 760 \times \cdot 169 = 342 \cdot 14$ units; of these we have utilised $2 \cdot 6638 \times 274 \cdot 6 \times \cdot 162 = 123 \cdot 62$, therefore the ratio is $\frac{123 \cdot 62}{342 \cdot 14} = \cdot 36$; only 36 per cent. of the total heat can be realised, and this is the ratio of the difference of temperature to the highest temperature, or $274 \cdot 6^{\circ} : 760$.

But suppose that, during expansion, additional heat were supplied to the air, so that its temperature should not change, how much heat should be added? The work done along the isothermal line would be $= 75$ lbs. $\times$ 10 c. ft. $\times$ 144 s. in. $\times$ $\log.^{\epsilon} (\frac{3}{1})$ = 118,650 foot-pounds, corresponding to $\frac{118,650}{772} = 153 \cdot 7$ units. The additional work done, over that due to the adiabatic curve, $118,650 - 95,638 = 23,012$ foot-pounds $= 29 \cdot 8$ units; adding this to the units of heat converted into work along the adiabatic curve, we have $123 \cdot 62 + 29 \cdot 8 = 153 \cdot 4$ units, very nearly the amount derived from the other mode of reasoning. Hence we see that the addition of heat, as the substance works, is incompetent to do any more work than if it were originally imparted. It has had the effect, indeed, of enabling the ten cubic feet of gas to do more work in the same apparatus, but it has not effected any economy in heat. Let us pursue this important matter a little farther. The expansion to three times along the isothermal leaves the air at 25 lbs. pressure, or $10 \cdot 3$ lbs. above the atmosphere, instead of $1 \cdot 27$ lbs. as in the case of the adiabatic; hence we have $9 \cdot 03$ lbs. of potential energy, which may be utilised by extending the stroke to

4·7 volumes, and an amount of work = 166,978 foot-pounds, corresponding to 216·3 units, will be realised, but still no more than is due to the heat imparted to the gas.

In the case of a gas, such as steam, near its point of condensation, the adiabatic curve cannot be followed, because the moment the temperature falls to the point where, at the particular pressure, condensation begins, the nature of the agent changes, and a portion of it becomes liquid. The theoretical curve of pressure would therefore be between the adiabatic and isothermal lines, because a very slight fall of pressure sets free a great deal of heat. For example, a change caused by cooling from 31 to 30 lbs. pressure in a body of steam weighing 3·27 lbs. would condense $\frac{1}{10}$th of a pound, and the heat liberated would be competent to raise the temperature of the steam 79°. It is impossible, mathematically, to define the curve of pressure that steam would actually register, but this need inspire no regret, because the conditions are such as never can occur in practice. It is plain, however, that whatsoever changes take place in the relative proportions of liquid and vapour, they can have no effect on the fundamental proposition that the quantity of work done by steam depends only upon its loss of heat. Steam at 150 lbs. absolute pressure and 818° temperature may be worked down to 2 lbs. pressure and 586° temperature, but the percentage of duty to be obtained from the total heat of such steam can never exceed $\frac{818-586}{818}$ $= \cdot 28$, or, in other words, 72 per cent. of the power cannot be realised.

In all the above investigations we have been dealing with an ideal state of things. All heat engines work in cycles, the vessels containing the working substances are more or

less pervious to and retentive of heat, hence, as in the case of the cylinders of hot-air or steam engines, they are colder than the working substance when it enters and hotter when it leaves, so that the pressure curves are generally between the isothermal and adiabatic. Steam-jackets have been introduced in order to keep up the temperature and cause the working substance to expand along the isothermal line. What has already been said on this subject shows that there is no theoretical gain in steam-jackets; they can produce no effect whatever upon the fact that every foot-pound of work is represented by a corresponding absorption of heat; but a steam-jacket makes the curve of pressure follow more nearly the isothermal line, and so enables the same engine to do a larger quantity of work, without sensibly increasing friction and other resistances, and to use a higher rate of expansion to obtain the same power, which, in the case of steam, implies higher initial pressure and consequently temperature, and a greater fall of the latter in the working substance, and hence economy.

A practical application of the laws relating to the compression and expansion of gases is found in Colonel Moncreiff's hydropneumatic carriages for disappearing guns. In Colonel Moncreiff's system the gun fires over a parapet, and recoils backwards and downwards into an emplacement, where the gun and its detachment are completely protected by the earthwork of the battery, and where loading can go on in safety. The energy of recoil, and work due to the falling gun, are transferred to a ram working into a hydraulic cylinder, the water in which is in communication with an air vessel by means of a passage fitted with a self-acting valve, opening from the cylinder into the air vessel. The air vessel is about $2\frac{1}{2}$ times the

volume of the ram, and is charged with air at such a pressure that the work of further compressing it shall be equal to the work due to the discharge and falling gun. Recoil taking place in but the fraction of a second, heat has no time to escape, the air pressure increases therefore nearly in proportion to the ordinates of an adiabatic curve. While the gun is being loaded the air cools, and assumes the pressure due to the temperature of the surrounding atmosphere; and when the gun is raised briskly into the firing position, which is done by opening a communication between the water in the bottom of the air vessel and the hydraulic cylinder by means of a cock, the air expands, also nearly according to the ordinates of an adiabatic curve. After the gun has been up two or three minutes, the pressure of the air rises, and becomes stationary at that due to the temperature of the atmosphere. If the gun be raised or hauled down slowly, the pressures vary according to the isothermal curve. The energy of the discharge transferred to the hydropneumatic apparatus has been converted into heat, which has been slowly dissipated in the atmosphere, and a portion of that heat has been requisitioned again and converted into the work done in lifting the gun.

But it may be justly objected that up to the present only a particular case of conversion of heat into work has been considered, and that no general theory can safely be based on an isolated example. The objection is quite just, and therefore we proceed to examine the great doctrine, first propounded in 1824 by Sadi Carnot, but only recently fully appreciated and brought into notice.

Before we can determine the efficiency of any machine, we must be sure that it is so adjusted as to be producing as much work as it is capable of doing. To ascertain

whether a machine is so adjusted, Carnot hit upon the idea of a reversible engine. He argued that if a heat engine took in a certain quantity of heat, and gave out a definite amount of work, that, if the engine were perfect, it could be reversed, and by application of the same work would give back to its source the exact quantity of heat which had at first produced the work. For supposing A were an engine as above described, and yet that there was another engine, B, more perfect—that is to say, capable of producing more work than A from the same quantity of heat. Let the two engines be coupled, and let B drive A in the reverse direction. If B is a superior engine to the perfectly reversible engine A, then B would do more work than A, and as A converts all the work into heat, it follows that B would return more heat to the source through A than it took from the source, there would therefore be a continued accumulation of heat due to the working of the coupled engines, which is contrary to experience and to the law that neither matter nor energy can be created or destroyed, so that an engine which is completely reversible, *is* a perfect engine, and extracts all the work that can be got out of the heat imparted to it.

We will now take a particular case of an engine making a complete cycle, that is, making one double stroke during which useful external work is done, and the engine returns at the end of the cycle to exactly the same state as it was at the beginning. We are now engaged in considering a purely ideal engine, one that can never be constructed, because we have no materials possessing the properties of perfect transparency and perfect opaqueness to heat, which must be assumed, so we must be content to accept, merely as conceivable, the alterations in the nature of the material of the cylinder which will be indicated.

It is usual to express the changes which take place by means of algebraic symbols, but to work out a case in figures is preferable, because the reality of the doctrine will impress itself more clearly on the mind, and will at

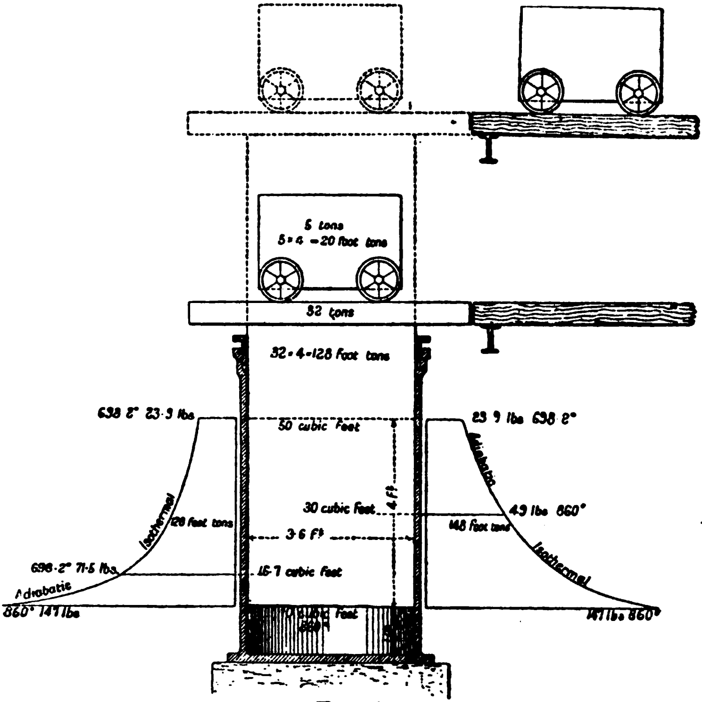


FIG. 22.

the same time serve as a practical application of the theories which have been already discussed.

On the diagram Fig. 22 is represented a vertical cylinder about 3·6 ft. in diameter, or having a cross section of 10 sq. ft.; the length is 5 ft. Sliding air-tight in the cylinder is a ram, loaded on its upper end so that the

permanent weight of the ram, including the pressure of the atmosphere, is equal to about 32 tons. A movable load of 5 tons, which the apparatus is constructed to raise to a height of 4 ft., is fitted with wheels, so that it can be rolled off the head of the ram when raised to the proper height. The ram is arranged so that it cannot fall lower than within one foot of the bottom of the cylinder, leaving there 10 cubic feet of space. It is immaterial what gas we employ for working this machine; we will, therefore, use air, as being most conveniently obtainable. We compress the air, and heat it by some means till we obtain a pressure of 10 atmospheres, or 147 lbs. per square inch, and a temperature of 400° Fahr., or 860° absolute. The material of which the cylinder and ram are made does not allow any heat to escape. The upward pressure on the bottom of the ram is nearly 95 tons, so that if we release the ram, it will rise with considerable velocity, on account of the accelerating force being 95 tons acting on a weight of 37 tons only.

We arrange matters so that while the first half of the stroke, or 2 feet, is being accomplished, the air is kept heated by some means, so that it should expand and press upon the ram according to the ordinates of an isothermal curve for 860°. On each side of the cylinder is drawn an indicator diagram, in which the horizontal ordinates of the curves show the pressures at any point; the curves on the right hand side give the pressures during the up stroke. If we continued heating the air farther, we should have an excess of power, so, at half stroke, when the pressure has fallen to 49 lbs., the supply of heat is cut off, and the air will continue to expand, falling in temperature and in pressure according to the ordinates of an adiabatic curve, till at the end of the

stroke the pressure has fallen to 23·9 lbs., and the temperature to 698·2°, and the gas occupies 50 cubic feet. The terminal pressure on the ram only gives an upward push of 15·3 tons, so that the stroke is completed by virtue of the momentum imparted at the beginning, and the ram must be held up at the finish of the stroke if it is desired to stop the machine. The work done is represented by the area of the diagram on the right hand side, and is equal to 148 foot-tons, which is also the work of raising the ram and load, weighing 37 tons, four feet, hence the machine will come to rest at the height named. We now roll off the load of 5 tons which it has been our object to lift, and we must get the ram, now reduced to 32 tons weight, back into its original position ready for another stroke; this would represent work = 128 foot-tons, and must be balanced by the resistance of the gas to compression from 50 cubic feet to 10 cubic feet. The upward pressure on the ram, we have already found, is reduced to 15·3 tons, so that an accelerating force of nearly 17 tons is available to start the downward motion.

If we arrange so as to prevent all escape of heat due to the work of compression, the pressures will rise according to the ordinates of an adiabatic curve, and the work done will be about 175 foot-tons, which is 47 foot-tons more than the weight of the ram is competent to perform, and therefore it would not reach the bottom of its stroke. If we arrange so as to prevent the temperature rising above 698·2°, the initial temperature of the return stroke, the pressures will rise according to the isothermal curve of 698·2°, and the work done will be 123 foot-tons, which will be too little to absorb the work of the falling ram; therefore we must stop the escape of heat after a time, and allow the plunger to complete its down stroke so that the

pressures shall rise as ordinates of an adiabatic curve. We must commence retaining the heat at such a point that the pressure will rise to 147 lbs., and the temperature to 860°, at the end of the stroke, and leave the air in exactly the same condition as it existed at the commencement of the up stroke. The point at which the exit of heat is to be stopped is easily calculated by applying the formula—

$$t_1 = t\left(\frac{v}{v_1}\right)^{\cdot 408}$$

Therefore $v_1 = \dfrac{v}{\left(\dfrac{t_1}{t}\right)^{2 \cdot 45}}$

We know $v = 10$ c. ft., $t = 860°$, $t_1 = 682 \cdot 2°$, and therefore $v_1 = 16 \cdot 66$ cubic feet; consequently compression along the isothermal line, as represented on the left side of the diagram, will go on for $3 \cdot 33$ feet, and along the adiabatic for $\cdot 67$ feet.

When the ram reaches the position from which it started, we have the air in exactly the same condition as to quantity, temperature, and pressure, as it was at the beginning of the up stroke, there is no change in the mechanism; it is plain, therefore, that the useful work done of raising 5 tons 4 feet could not be due to the air, for no change has taken place in it. The changes which have taken place are:—1st, we have added heat during the first half of the up stroke, and secondly, have suffered heat to escape during $3 \cdot 33$ feet of the down stroke.

How much heat has been communicated to the air and again abstracted from it? It is clear that the air, in expanding to half the stroke without change of temperature, must have taken in the quantity of heat equivalent to the work done. We measure or calculate the area of the

figure representing the work done, and find it to be 232,500 foot-pounds. Dividing by 772, Joule's equivalent, we obtain that 301·2 units of heat must have been communicated to the air.

Next, because the temperature of the air did not rise during the first 3·33 feet of compression in the down stroke, it is clear that the amount of heat due to the work done of 32 tons falling 3·33 feet must have been taken off. Measuring the figure bounded by the isothermal curve, we find it to have an area of 188,880 foot-pounds. Dividing by 772 again, we get 244·7 units. We therefore added 301·2 units of heat, and abstracted 244·7 units; what has become of the difference, 56·5 units? Multiplying by 772, we get 43,618 foot-pounds, which is very nearly the work of lifting the load of 5 tons which we have raised to a height of 4 feet, hence 56·6 units ot heat have been converted into the potential energy of 5 tons with respect to a fall of 4 feet. Next observe that in this perfect engine we have expended 301·2 units of heat to convert 56·5 units into useful work; the proportion is only 19 per cent. The temperature of the air fell from 890° to 608·2°, a difference of 161·8°; the ratio of this difference to the absolute temperature of the air at the commencement is also 19 per cent., and so we establish this fundamental law of the conversion of heat into useful work, that the proportion of heat imparted to or inherent in the working substance which can be converted into useful work is the proportion which the fall of temperature bears to the original absolute temperature. Let H = heat imparted to or inherent in the working substance, and T and t the absolute temperatures at the beginning and end of the operation, then available work $= \mathrm{H}\,\frac{\mathrm{T}-t}{\mathrm{T}}$.

In addition, it should be noted that the nature of the working substance, its absolute temperature at starting, the mode in which it is heated and cooled, and the mechanical arrangement by which the conversion is effected, have none of them anything to do with the result.

It is true that, in practice, we cannot attain to the duty done by our ideal engine, but we can apply the law just explained, and determine what is the limit which we may hope to reach. In some cases, such as the generation of steam, where no machinery is interposed, we attain very nearly the theoretical duty.

Carnot illustrated his theory by referring to the arrangement for utilising a fall of water. Suppose Fig. 23 a reservoir on a hill side, from which a pipe is led into a turbine part of the way down the hill, and from thence the tail race is carried into the sea. The mean sea level is the lowest point to which water can fall, and may be compared to the absolute zero of temperature. Let the height of the water in the reservoir above the sea be T, the height of the water in the tail race at the mill be t, and the weight of water falling per minute W. In the reservoir, the potential energy of the water per minute, with reference to the sea level, is $W \times T$, and that is also the maximum kinetic energy with which it is capable of being endowed, so that a perfect disposition could only be attained by placing the mill at the sea level. The potential energy of the water in the pool at the mill is W t, hence the energy utilised is $W\,T - W\,t = W\,(T-t)$, that is: the weight of water multiplied by the nett fall, and the proportion which this bears to the absolute maximum energy is $\frac{W\,T - W\,t}{W\,T}, = \frac{T-t}{T}$, or in other words, the propor-

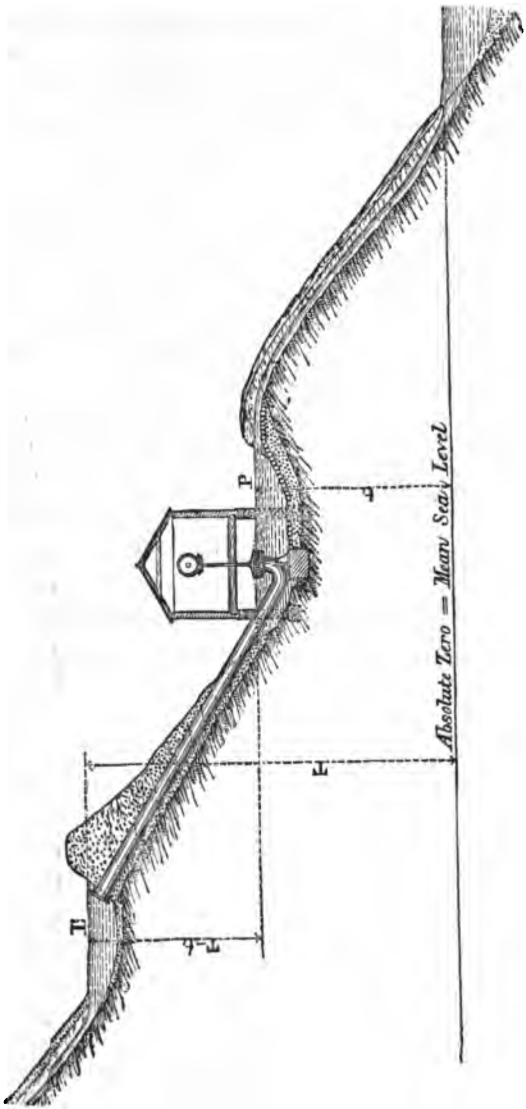


FIG. 23.—ILLUSTRATION OF CARNOT'S DOCTRINE, 1824.

tion which the fall actually utilised bears to the maximum possible fall. Carnot's theory may be reasoned out in a common sense way thus:—The quantity of heat, or of energy, given out by a gas as it cools, is in direct proportion to the change of temperature. It is obvious that the only way to get all the energy out of a gas is to cool it down to absolute zero, and therefore, if you only cool it, say, to 1-6th of the way to zero, you can only get 1-6th of the possible work.

It has been stated that it is immaterial what the working substance may be. We have made use of air and gases, but a true heat engine may be constructed of metal.

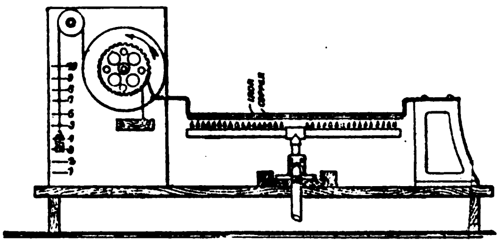


Fig. 24.

Fig. 24 represents an engine, the essential part of which is a compound bar composed of a strip of copper rivetted underneath a strip of iron. One end of the bar is rigidly fixed to a stand, the other end is free, and actuates a ratchet wheel by means of a pawl. A second fixed pawl prevents the wheel running back, and to the wheel is fastened a drum, round which is wound a cord, by means of which it is proposed to raise a weight.

When the compound bar is heated by means of gas jets, the copper expands more than the iron, the bar consequently curls up, and the ratchet, at its end, carries

round the wheel, and so lifts the weight. The bar is now in the same condition as the ideal engine when it had raised the load of five tons; it must be got back again to its original position, so as to complete the cycle and leave the engine ready for the next stroke. This can only be done by cooling the bar, for which purpose it can be immersed into a tank containing wetted waste. When this is done it returns instantly to its original condition, and is ready for another stroke. By repeating the operation the weight may be lifted as high as we please. In this case, also, it would be found that the amount of heat communicated to the bar is more than that abstracted from it by the amount converted into the mechanical work of raising the weight.

According to Newton's third law of motion, to every action there is an equal and opposite reaction, and as we believe, according to Sir Humphry Davy, that the molecular motion which we call heat obeys the ordinary laws of motion, so we conclude that the ideal heat engine is perfectly reversible. The action of the heated air had for its reaction the raising of the load and the ram, therefore if the falling of the load and ram were the action, the compression of the air and the development of a certain amount of heat would be the reaction. Again, the action of the falling ram finds its equivalent in the reaction of the compressed air and the liberated heat, consequently when the air is permitted to expand, and is suitably warmed, the reaction will be the return of the ram to its original position ready to receive another load. The balance of this reverse operation will be the accumulation of an amount of heat represented by the work done by five tons falling four feet.

It will be observed that a necessary condition of action

is a fall of temperature. The ideal engine finished its work, which was all done in the *up* stroke, at a lower temperature than it began; and in the heated bar, though the reverse apparently took place, it was only because the normal condition of the bar is to be cold. Had we begun with the bar like the air in its heated state, the work could have been done by cooling.

We are now enabled to enunciate the second law of thermodynamics, which is—"It is impossible to transform any part of the heat of a body into mechanical work, except by allowing heat to pass from that body into another at a lower temperature."

It is difficult to exaggerate the importance of the principles which we have been discussing. Had the doctrine of Carnot been earlier recognised and known, a vast saving of fruitless expenditure in toil, money, and hope deferred would have been saved to unhappy inventors, who, through ignorance, have been lured on to attempt results in the working of heat engines, which are just as much beyond our reach as the transmutation of metals or perpetual motion.

CHAPTER IV.

In the previous chapter was explained the great principle, first laid down by Sadi Carnot in 1824, that in a heat engine the effect depends solely and entirely upon the fall of temperature caused by the external work done by the working substance, or upon the heat which it is the instrument of converting into work, and not in any way on the nature of the substance, its absolute temperature, or on the mode in which it was heated or cooled.

We know by experience that if we desire to heat a body, we must bring it into relations with some body hotter than itself, and then the more energetic molecular motion of the hotter body will gradually be transferred to the colder one, until an equality is attained. Now, what is true of the transfer of invisible molecular motion from one body to another, is equally true of the transfer of the invisible molecular motion of heat, and its change into the coarser and apparent motion of mechanical work. If an insulated hot body be doing external work, its temperature must fall, just as the swing of the single ball in the ball frame is reduced by transfer of its energy to the other balls.

The law of Carnot is therefore universal, that where a hot body does external work, a corresponding quantity of heat disappears as heat, and the amount of work done when no heat is added, is in proportion to the fall of tem-

perature, because the quantity of heat contained by the working substance varies as the temperature, when there is no change of physical state.

The laws of Carnot, as stated by himself, are the following:—

1. The motive power of Heat is independent of the agents employed to develop it, and its quantity is determined solely by the temperatures of the bodies between which the final transfer of caloric takes place.

2. The temperature of the agent must, in the first instance, be raised to the highest degree possible, in order to obtain a great fall of caloric, and, as a consequence, a large production of motive power.

3. For the same reason, the cooling of the agent must be carried to as low a degree as possible.

4. Matters must be so arranged that the passage of the elastic agent from the higher to the lower temperature must be due to an increase of volume, that is to say, the cooling of the agent must be caused by its rarefaction.

The last part of the fourth law should read, "the cooling of the agent must be caused by the external work it performs." Carnot was ignorant of the cause of the fall of temperature of gases expanding and doing work, and he held the emission theory of heat. Our admiration for the clearness of his views is greatly heightened by the consideration of the limited knowledge available in his time.

The sources of heat on the surface of the earth are numerous, and, in their application, they give out the energy potential in them not only as heat, but in other forms, such as light, electricity, mechanical and molecular motion, chemical effect; and all these have an exact mechanical equivalent. Conversely, mechanical power may be transformed into other forms of energy.

The gas burning in a room owes its brilliancy to the heat engendered by the clashing together, in chemical union, of the constituent atoms of the gas and of the oxygen of the atmosphere. The burners not only radiate light, but also heat; they cause currents to form in the air of the room, and most of them send forth sound pulses, more or less loud, in all directions. If a thermopile be held next to a jet, the galvanometer instantly indicates that a current of electricity has been set up; the energy represented by light and radiant heat has been converted into a galvanic current.

The glass rod, with the ball suspended opposite one end (Fig. 14), will illustrate the converse principle. If it be rubbed energetically, a musical sound is produced; the power of the arm has set the rod into longitudinal vibration, as may be seen by the vigour with which the little glass ball bounds from its end; that vibration has communicated musical pulses to the air. In addition, the rod has become hot, and if the face of a thermopile be brought into contact with it, a portion of the heat-energy is transformed into an electric current, competent to deflect the needle of the galvanometer; and, further, the gold-leaf electroscope, which is connected to the rod by a copper wire, shows that frictional electricity has been developed. This experiment demonstrates how wide is the field in which we must search in order to collect all the reactions corresponding to any particular mechanical effort. The debtor side of the account is generally composed of only one item, but the creditor side is made up of expenditure in many directions, and in that respect bears a strong resemblance to the same side in ordinary financial transactions.

The ultimate source of all energy is the sun. We cannot stop to discuss the various theories as to whence the

solar heat originally came, and how the enormous waste continually going on is made good. We must content ourselves with the statement that the compound rays emitted by the sun warm the earth, producing vast movements of water, in consequence of evaporation and the formation of clouds, and so we have warmth, light, and moisture, upon which the growth of the vegetable and animal kingdom depends. Vegetation derives most of its food, not from the earth, into which its roots penetrate, but from the air. The lovely mantle of green leaves, which adorns the productive portions of our planet, is not intended to beautify alone: the vast surface exposed to the air has the property, under the influence of the chemical rays of the sun, of decomposing the carbonic acid in the atmosphere, of assimilating the carbon, converting it into the ligneous part of plants, and rejecting the oxygen, which is, however, essential to the life of animals, by whom it is inhaled, and, again rejected, restored to the condition of carbonic acid.

The quantity of carbonic acid in the atmosphere is relatively small, varying from three parts, by measure, to ten parts in 10,000, but, absolutely, the weight of carbon thus diffused is greater than all the carbon in the solid form on the face of the earth.

The sources of carbonic acid are the expirations of animals, the combustion of vegetable and animal substances, and emanations of a volcanic character. Wood contains from 46 to 55 per cent. of carbon, all derived from the atmosphere; and because the quantity of carbonic acid in the air is relatively so small, an immense leaf surface is necessary to collect sufficient for the growth of the plant. By long continued contact with moisture and warm air, wood slowly decomposes by combining with

oxygen, and is converted, according to circumstances, into vegetable mould, peat, lignite, or, finally, into coal, which, in the form of anthracite, consists of almost pure carbon.

The work done by the sun's rays in decomposing the carbonic acid of the air is very great. The energy which must be exerted to separate the carbon from its oxygen is the same as that developed by the combination of the same elements in combustion, and has been determined by experiment to be equal to about 14,500 units of heat per pound of carbon consumed. By an easy calculation, it can be deduced that every ton of carbon separated from the atmosphere in twelve hours involves energy represented by 1,058 horse-power expended by the sun; but as this energy operates over an enormous leaf surface, its effects are quite imperceptible to our senses.

The mechanical view to take of fuels is, that their component elements are in a state of potential energy with respect to the oxygen of the air, or, as in the case of explosives, with respect to each other, and that they clash together in combining with so much violence as to produce, in a high degree, the motions which we call light and heat. The energy of chemical combination has a strictly definite value for each kind of fuel, just like the potential energy of a body of water is a perfectly definite quantity with respect to its available fall.

The precise amount of heat developed in the combustion of fuel has been investigated by a great number of skilful experimenters. At the end of last century Lavoisier and Laplace, and in our own times Dulong, Despretz, Favre and Silbermann, Andrews, Berthelot, Thomsen and others have contributed to the determination of the laws of thermo-chemistry and to ascertaining the exact heat equivalent of various reactions.

In particular Favre and Silbermann, between the years 1845 and 1852, carried out a valuable series of experiments by means of a calorimeter, represented in Fig. 25. This apparatus consisted of a combustion chamber A formed of thin copper, gilt internally, and fitted with a cover through which solid combustibles could be introduced into the cage C. The cover was traversed by a pipe E connected by means of suitable pipes to a reservoir of the gas used in combustion, and by a second tube D, the lower end of which was closed with alum and glass, transparent but adiathermanous substances, which permitted the operator to watch the process of combustion without causing any loss of heat. For convenience of observation a small inclined mirror was placed above the peep-tube. The products of combustion were carried off by a pipe F, the lower part of which constituted a thin copper coil, and the upper part was connected to the apparatus in which the non-condensible products were collected and examined. The whole of this portion of the calorimeter was plunged into a thin copper vessel G, silvered internally and filled with water, which was kept thoroughly mixed by means of agitators, H. This second vessel stood on wooden blocks inside a third one I, the sides and bottoms of which were covered with the skins of swans with the down on, and the whole was immersed in a fourth vessel J, filled with water kept at the average temperature of the laboratory. Thermometers K, K, of great delicacy were used to measure the increase of temperature in the water surrounding the combustion chamber, for the quantity of heat developed by the combustion of a known weight of fuel was determined by the increase of temperature of the water contained in the vessel G. For ascertaining the calorific value of gases only, the cage C was removed and a compound jet N,

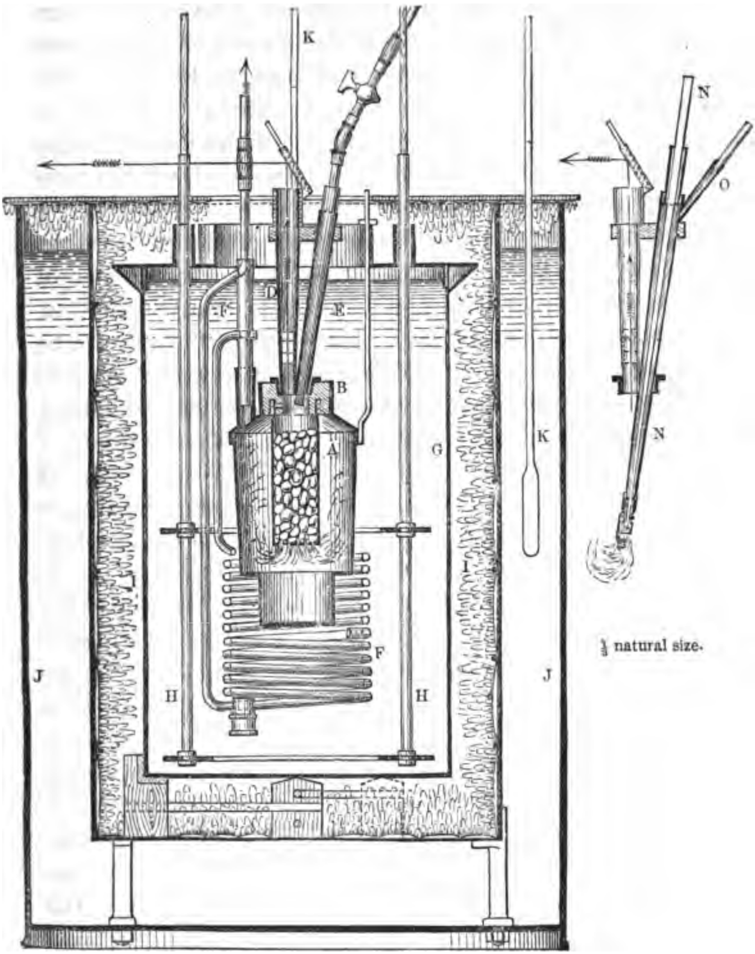


Fig. 25.

O, substituted for the single gas pipe, ignition being produced by some spongy platinum fixed at the end of the

jet. In addition to the calorimeter there was a vast array of apparatus for producing pure gases, and for collecting, weighing and analysing the products of combustion which escaped by the pipe F.

Favre and Silbermann adopted the plan of ascertaining the weight of the substances consumed by calculation from the weight of the products of combustion. Carbonic acid was absorbed by caustic potash, so also was carbonic oxide, after having been oxidised to carbonic acid by heated oxide of copper, and the vapour of water was absorbed by concentrated sulphuric acid. The adoption of this system showed that it was, in any case, necessary to analyse the products of combustion in order to detect imperfect action. Thus, in the case of substances containing carbon, carbonic oxide was always present to a variable extent with the carbonic acid, and corrections were necessary in order to determine the total heat due to the complete combination of the substance with oxygen.

Another advantage gained was that the absorption of the products of combustion prevents any sensible alteration in the volumes during the process, so that corrections for the heat absorbed in the work of displacing the atmosphere were not required.

The table on page 99 gives the calorific value and the composition of ordinary fuels.

The general conclusions arrived at by Favre and Silbermann, Berthelot, and others, are that, as a rule, there is an equality between the heat disengaged or absorbed in the acts, respectively, of chemical combination or decomposition of the same elements, so that the heat evolved during the combination of two simple or compound substances is equal to the heat absorbed at the time of their chemical segregation, and the quantity of heat evolved is the

PROPERTIES OF FUELS.

		Composition by weight.						Units of heat per lb.	Pounds water evaporated from and at 212°.	Pounds dry air to one pound of fuel.	Calculated rise of temperature due to combustion.	Units of heat per pound of complete fuel.
		Carbon.	Hydrogen.	Nitrogen.	Oxygen.	Sulphur.	Ash.					
	Atomic weight. . .	12	1	14	16	32						
1	Durham coke	93·78	..	..	..	·82	5·4	13,640	14·12	10·91	4,877°	1,145
2	Anthracite	90·39	3·28	·83	2·98	·91	1·61	14,698	15·21	11·53	4,856°	1,173
3	Newport steam coal . . .	81·47	4·97	1·63	5·32	1·10	5·51	14,143	14·64	10·99	4,830°	1,180
4	Wigan cannel coal	80·07	5·52	2·12	8·09	1·50	2·70	14,051	14·55	10·92	4,800°	1,179
5	Wolverhampton ten-yard seam	78·57	5·29	1·84	12·88	·39	1·03	13,390	13·86	10·41	4,765°	1,174
6	Petroleum	85·	15·	..	..	..	..	20,363	21·08	15·07	4,900°	1,267
7	Oak wood (dried at 284°) . .	49·95	6·	1·13	41·27	..	1·65	7,713	7·98	6·08	4,287°	1,089
8	Illuminating gas, by weight .	61·26	25·55	8·72	4·47	..	..	20,801	21·53	15·66	4,567°	1,249
9	Do. do. per 1,000 cubic feet, at 30″ pressure, 60° Fahr. = 29·685 lb. . . .	lbs. 18·19	lbs. 7·58	lbs. 2·59	lbs. 1·33	..	..	Per 1,000 cubic feet. 617,485	639	465	..	..
10	Gunpowder	Charcoal. 14·2	Water. 1·	Nitre. 74·7	..	10·1	..	1,300	..	None.	3,960°	1,300

measure of the sum of the chemical and physical work accomplished in the reaction.

The theories we have been discussing would naturally lead to the latter conclusion. The molecular energy set up by the conversion of the potential energy of the fuel into the kinetic form would most probably be expended in part, in the case of compound bodies, in the work of breaking up their structure before fresh combinations could take place, and, on the other hand, we can conceive chemical combinations of a nature that, on breaking up, would yield heat. Thus, carbon burned in protoxide of nitrogen, or laughing gas, N_2O, produces about 38 per cent. more heat than the same substance burned in oxygen; whereas in marsh gas, or methane, CH_4, the energy of combustion is considerably less than that due to the burning of the carbon and hydrogen separately.

NOTES TO THE TABLE OF FUELS.

By W. H. Deering.

Column 2.—Units of heat per 1 lb. consumed.—The numbers given under this column are calculated with values for the heat of combustion of hydrogen, of marsh gas, and of ethylene, which assume that the water produced by their combustion remains in the gaseous state; an assumption rendered necessary for the requirements of column 3, where the products of combustion are to heat water already at 212° Fahr.

The heat of combustion of carbon is taken as 14,544 lb.-degrees (Fahrenheit), that of hydrogen as 53,339 lb.-degrees, and the hydrogen available as fuel is supposed to be given by:—Total hydrogen—⅛ oxygen.

No allowance is made in the calculation of the coals for evolution of heat in the burning of the small quantity of sulphur, there not being adequate data.

The heat of formation of the different coals not being certainly known, these calculated numbers for heat of combustion will be useful for comparison, but must not be taken as the quantities that would actually be obtained.

In the case of illuminating gas (No. 8), which is taken as dry, the total heat of combustion, given under column 2, is calculated from the con-

stituents: hydrogen, marsh gas, carbonic oxide, &c., using the respective experimentally obtained values.

In the case of petroleum, the numbers given for the calorific power of petroleums are corrected experimental numbers, obtained by Deville, who worked on a large scale.

The correction of Deville's experimental number for calorific power consists in the deduction of the latent heat of the water, produced by the combustion of the petroleum; he having cooled his chimney gases, and liquefied the water.

Deville determined the calorific power of Baku petroleum, and found it to be somewhat higher than that of Pennsylvanian petroleum. The experimental number was 700 Fahrenheit units (or 1–26th) lower than the number obtained by calculation from the per-centage composition of the petroleum.

Column 4.—Weight of dry air required for combustion.—An allowance is made for the air required for the combustion of the sulphur contained in the coal and coke. It is regarded as half being in combination in the non-mineral part of the coal, and half being present as iron pyrites. The sulphur is supposed to be burnt to SO_2, and the iron to ferric oxide, when on the above suppositions 1 lb. sulphur requires 4·89 lbs. of air. It does not much matter if the fundamental suppositions are not wholly correct, as 1 per cent. of sulphur so calculated requires only 0·05 lb. of air, when 1 lb. of coal is burnt.

Column 5.—Maximum Rise of Temperature.—The specific heats of the products of combustion: carbon dioxide, gaseous water, and of the nitrogen of the air, used in the calculation of maximum rise of temperature are 0·217, 0·48, 0·244 respectively; and are the specific heats of those gases at constant pressure.

The numbers given under this column have some value for the purpose of comparison, but must not be taken as temperatures actually attainable. First, because dissociation of the elements of CO_2 and H_2O would take place at temperatures much below those given; the consequence of which would be that, at the hottest place of combustion, there would be some unburnt, and there unburnable, carbonic oxide and hydrogen.

Secondly, because the specific heats of gaseous water, of carbon dioxide and of nitrogen, are probably higher at the maximum temperatures of the combustion of the different fuels, than the values used for the calculation of column 5. The rise with temperature of the specific heat of carbon dioxide has long been known to be very considerable even at low temperatures, and recent researches of Berthelot and Vieille render it more than probable that there is also a great rise in the specific heats of gaseous water and of nitrogen at high temperatures. The use of these higher values for the specific heat of the gases mentioned would, of course, lower the calculated maximum rise of temperature.

Nearly all fuels consist of carbon, hydrogen, and oxygen. It is convenient to reduce the hydrogen to its heat equivalent of carbon. Hydrogen, in burning, develops 62,032 units per pound, while carbon develops only 14,544, so that hydrogen gives out $4 \cdot 265$ times more heat than carbon, and may be thus represented by it, $H = 4 \cdot 265\ C$.

It has already been remarked that, in dealing with gases near their points of liquefaction, great circumspection must be used. The case of the combustion of hydrogen offers an excellent illustration. Favre and Silbermann condensed the products of combustion, and so determined the total quantity of heat developed, which included the latent heat of evaporation; but in furnaces, the water formed in the combustion of hydro-carbon fuels passes off in the state of vapour, hence the latent heat of evaporation is not available. One pound of hydrogen burns to 9 lbs. of water, the latent heat of which, at 212°, is 966 units, hence we must deduct $966 \times 9 = 8{,}694$ units from the tabular value of the heat due to the combustion of hydrogen, which leaves only 53,338 units available; therefore the value in terms of carbon is $H = \frac{53338}{14544}\ C = 3 \cdot 67\ C$, or 14 per cent. less than if the vapour formed were condensed to water. I am indebted to Mr. Deering, of the Chemical Department of the Royal Laboratory at Woolwich, for pointing out to me this important correction, which appears to have escaped the acuteness of even so careful and profound a writer as the late Professor Rankine.

The oxygen in fuel exists, for the most part, united to hydrogen in the form of water, and is, therefore, already in chemical union with a portion of the hydrogen, and incapable of further work; hence the equivalent weight, or one-eighth of the oxygen, should be deducted from the

hydrogen before it is reduced to its equivalent value of carbon. The calculation takes this form, when the water passes away in the state of vapour—

$$\text{Heat of combustion} = 14544 \left\{ C + 3 \cdot 67 \left(H - \frac{O}{8} \right) \right\}$$

The formula does not always apply exactly, as, for example, in the case of marsh gas, where the heat developed is less than that due to the separate combustion of the carbon and hydrogen, namely, 23,513 units only, against 26,416, the theoretical amount.

The case of gunpowder is peculiar in every way. The chemical reaction which takes place is not very well understood. Powder contains all the ingredients of combustion in itself, and is not dependent on the oxygen of the air. The conversion into gas is very imperfect, only 43 per cent. becoming gaseous, while 57 per cent. is shattered into a very finely divided state, ultimately forming the smoke which characterises the explosion of powder.

In comparing the calorific value of fuels, it is desirable to associate with them the air necessary for their combustion, because, by doing so, self-contained combustibles, such as explosives, can be brought into the category. When the chemical composition of any fuel is known, it is easy to calculate the quantity of oxygen required to ensure complete combustion, and remembering that this gas constitutes about 22 per cent. of the weight of the atmosphere, the weight of air is easily arrived at. In the table on page 99 is given the chemical composition of different kinds of fuel, the units of heat derived from the complete combustion of a pound of each, the corresponding weight of water evaporated from and at 212°, and the weight of air required for combustion.

It will be observed that gunpowder stands apparently in a very unfavourable position, yielding only 1,300 units against nearly 15,000 for some kinds of coal, but the comparison is not fair, because the other kinds of fuel are in an imperfect state. To make them self-contained, like gunpowder, we should add to each the weight of air necessary for its combustion, and then we get a singular uniformity in the units of heat per pound of complete fuel, as may be seen by inspecting the last column in the table; and as in gunpowder there is no less than 57 per cent. of inert matter, so in the complete fuels no less than 72 per cent. is inert under the most favourable circumstances.

Berthelot's first law of thermo-chemistry has been already given. Two others must be added.

2. When a system of bodies, simple or compound, starting from a given condition, undergoes chemical changes which bring it into a new condition without producing any mechanical effect on external bodies, the amount of heat evolved or absorbed as the total result of these changes depends solely on the initial and final states of the system, and is the same whatever may be the nature or order of the intermediate states.

An illustration of the application of this law occurs in the combustion of carbon when in thick layers. Under such circumstances the fuel near the bars is completely oxidised, and passes into the mass of glowing carbon above it in the form of carbonic acid gas, which is composed of one equivalent of carbon united to two equivalents of oxygen. In the mass of heated fuel the carbonic acid yields up one equivalent of oxygen to the carbon, and reaches the surface of the fire in the form of carbonic oxide, and here, meeting with a supply of air, the oxide burns, with a pale blue flame, to carbonic acid again.

Berthelot's second law tells us that the intermediate reaction in the mass of glowing fuel does not affect the final result as far as the development of heat is concerned, so that, for the purpose of estimating the thermal value of fuel, all we require to know is its original composition, and the final chemical nature of the products of combustion.

3. Berthelot's third law states, "That in any chemical reaction between a system of bodies, not acted on by external forces, the tendency is towards that condition, and towards those products, which will result in the greatest evolution of heat."

This law, therefore, furnishes a guide when calculating the heating power of fuels of complex structure, and which may oxidise into various substances, as to which combination is most likely to take place, for it tells us that we must select those reactions which will yield the most heat.

The table of the calorific value of fuels has been calculated in accordance with the above laws. The heat equivalents of the elementary bodies, of marsh gas and olefiant gas, have been arrived at by direct experiment. The effects due to the explosion of gunpowder have been derived from the splendid and truly practical experiments of Sir Frederick Abel and Captain Noble. Mr. Deering has very kindly revised my calculations, and made some important corrections, based upon the most recent information we possess respecting the chemistry of fuels.

For the purpose of applying the doctrine of Carnot to the conversion of heat into useful work, it is necessary to determine the highest temperature which can be obtained by chemical reaction.

It is much to be deplored that we have not, as yet, a trustworthy pyrometer capable of indicating temperatures above the melting point of platinum. We are therefore

reduced to the necessity of being content with calculations. In these calculations there are several elements of uncertainty.

First, as to whether combustion is complete; secondly, as to the quantity of air entering the furnace; thirdly, as to whether the specific heats of the gases are not subject to variation at very high temperatures; and lastly, the part played by dissociation. There is a certain temperature below which the energetic chemical reaction, which we call combustion, cannot take place. Thus, coal-gas cannot be ignited below red heat, say 1,000°, and carbon requires a much higher temperature. Anything in the arrangement of a furnace which tends to cool the fuel below the temperature of combustion will lead to imperfect action.

Sir Humphry Davy availed himself of this fact in constructing his safety lamp. Explosive gases, though they freely pass through the meshes of wire gauze, are so cooled by contact with the comparatively cold metal, and by its high radiating powers, that though they may be burning on one side of the gauze, the combustion ceases as the gases pass through.

This may be illustrated by holding pieces of half-inch gas pipe, of lengths varying from $\frac{1}{2}$ inch to 6 inches, over an ordinary gas jet turned down low. It will be found that the flame will burn through the shorter pieces, while the longer ones will extinguish it. The reason is that in the former case the surface of the tube is not sufficient to abstract the heat from the flaming gas, so as to lower the temperature below that of combustion, while in the latter case it is. That the nature of the gas has not been altered in any way, is proved by the circumstance that it can be lighted on issuing from the top of the tube, which had proved itself competent to extinguish it.

In the construction of furnaces, the facts above stated must not be lost sight of. So long as chemical reaction is taking place, all that tends to cool any portion of the gas should be avoided.

Mr. Frederick Siemens has carried this principle into practice with great success in the regenerative gas furnace. It was formerly considered that the smaller the furnace, and the closer the flame approached the objects to be heated, the better would be the result, but Mr. Siemens has boldly deviated from this doctrine. He has greatly enlarged the volume of the furnace. He introduces the gas and air at a moderate distance from the sides, bottom, and top, and increases the span of the flame so as to insure complete combustion before the opposite side of the hearth is reached. The flame thus forms an isolated body, acting by radiation alone from the brilliantly incandescent particles of carbon, and the practical results attained are a higher temperature, due to complete combustion;—an increased durability of the furnace, due to the circumstance that the firebrick is not exposed to the erosion caused by the friction of the highly heated gases and by the solid particles carried along by them;—and, lastly, less deleterious effect upon the substances being heated. The same principle he has applied to boiler furnaces. By placing rings of firebricks at intervals in the flues, he keeps the flame from contact with the boiler plates. It parts with its heat by radiation alone, until the chemical reaction is complete, and then the heat may be abstracted from the products of combustion by contact, either in passing through small tubes or in any other way.

By constructing a model flue of mica with internal brass rings at intervals, Mr. Siemens has exhibited the prin-

ciples he contends for in a very elegant manner by means of an ordinary gas jet.

The method of heating furnaces by radiation is specially applicable when the flame is luminous, that is to say, charged with white-hot particles of carbon. A pale non-luminous flame, such as is produced by a Bunsen burner, has very little radiating power, because air, nitrogen, and carbonic acid, which form the bulk of such flame, are very

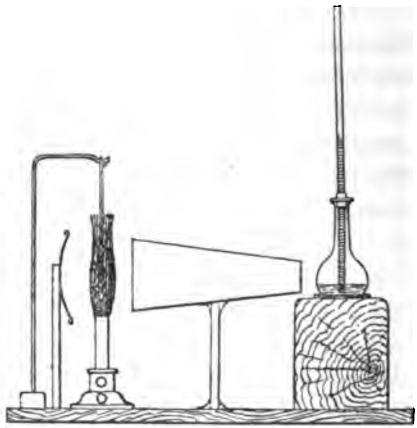


Fig. 26.

bad radiators of heat. The vapour of water is a good radiator, but it forms a very small portion of the products of combustion. Solid carbon, on the other hand, is an excellent radiator and absorber, and on that account a mass of flame charged with it will radiate heat powerfully. If a Bunsen burner (Fig. 26) be arranged so that the radiation from the flame can be concentrated, by a concave mirror and cone, on the blackened bulb of a large air thermometer, it will be found that the luminous and com-

paratively cold flame, resulting from an insufficient supply of air, will produce about the same effect as the intensely hot non-luminous one due to complete combustion; but if a spiral of wire be hung in the non-luminous flame, it begins to glow and to radiate its intense heat powerfully, causing the thermometer to rise rapidly.

Smoke in furnaces is not altogether an evil, because it serves the purpose of the spiral wire; it improves the radiating powers of the hot products of combustion, and by so doing compensates for the loss of heat due to the imperfect combustion by which it is produced.

In an ordinary furnace the fuel is in the most disadvantageous condition for complete combustion. It lies in large lumps loosely on the grate, with large and irregular interstices, through which the air and gases evolved have to make their way. In many places the streams of air are so thick that they do not come intimately into contact with the fuel at all, and pass through nearly unchanged, hence, as a rule, a large excess of air, amounting generally to at least 50 per cent., has to be admitted. In addition, the combustible gases evolved are, in places, cooled below their temperatures of combination by contact with large masses of air, and hence free carbonic oxide and particles of unconsumed carbon are generally found associated with the products escaping by the chimney.

By mechanically subdividing the fuel, and mixing it intimately with only the proper weight of air, the completeness and intensity of combustion may be greatly enhanced. Such a disposition we have in Mr. Crampton's dust-fuel furnace (Fig. 27). The fuel is reduced to the finest possible state of subdivision—so fine as to pass through a sieve of 100 meshes to the inch—by means of a disintegrator or a pair of mill-stones; it is then conveyed

into a hopper U, furnished with agitators V, which force it through an opening X, the width of which can be regulated at pleasure, into a pair of rollers W, which feed the

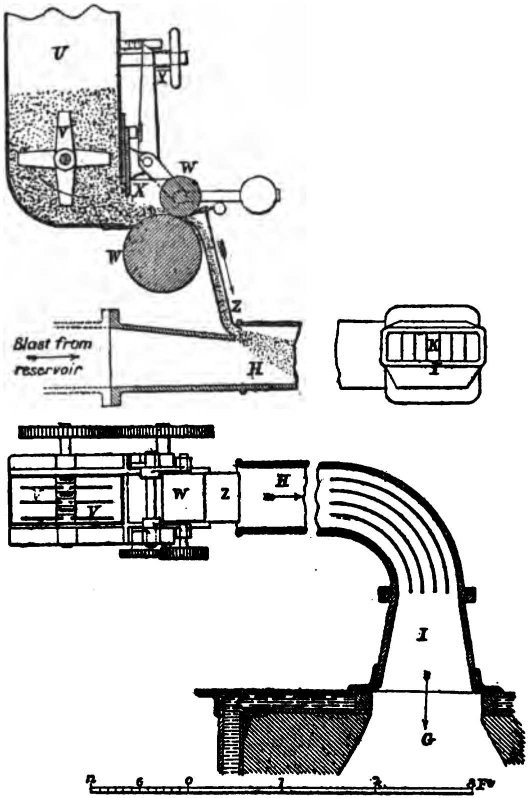


Fig. 27.

fuel at a uniform rate into a slit Z in a pipe H, along which a blast of air is passing. The dust mixes intimately with the air, and is carried along by it into the furnace G, where

it at once flashes into flame, of a temperature so intense that wrought iron can be easily melted. Simple as the process is, it has taken the inventor many years to overcome the minor difficulties which surrounded the practical application. One of these consisted in turning corners with the blast-pipe. The particles of coal, in obedience to the first law of motion, tended to maintain a rectilinear course, and could only be turned from it by the bent sides of the pipe; the consequence was that where a bend occurred, the coal-dust separated from the air, and collected along the concave side of the pipe. By introducing a number of parallel curved partitions into the bend, this action was, in a great measure, neutralised. Another difficulty lay in the erosive action of the particles of solid fuel on the brick lining of the furnace, but this has been overcome by the use of water-jackets, and by the proper direction given to the flame. Fig. 28 represents a revolving puddling furnace which was tried successfully at the Royal Arsenal, Woolwich. D is the fixed mouth of the furnace into which the blast of air and coal-dust is introduced by the pipe H, and the opening G. B is a hearth revolving on rollers C, and consists of a refractory lining surrounded by a water-jacketed casing. The flame takes the course indicated, and escapes to the chimney by the lateral opening D in the fixed mouth-piece. The metal to be puddled is introduced into the revolving portion, and assumes ultimately the form A. A current of cold water is caused to circulate through the jackets by means of the pipes, P, R, and E. It is obvious that the proportion of air and fuel, and the rate at which both are supplied, can be accurately adjusted, and, as a matter of fact, Mr. Crampton finds that he can use the theoretical proportion of air required by the coal, and at the same time secure complete

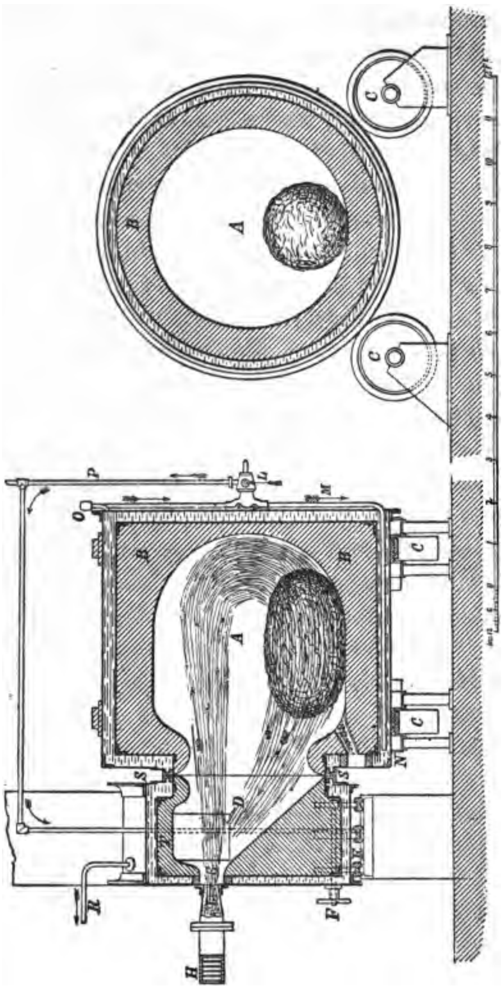


FIG. 28.

combustion and total absence of smoke. The consequence is, that the chemical action is so energetic that a very high

temperature is reached at once with cold air and cold fuel. The manual labour connected with the system is really confined to supervision; it would seem therefore peculiarly fitted for steam ships, where stokers are exposed to so much hardship, especially in tropical climates, and where their cost is a serious item in the expenses of a voyage. The tonnage necessary for the accommodation of stokers, and the stores required by them, would probably exceed the space which grinding machinery would occupy. Up to the present, however, no successful application of the system has been made to boilers, chiefly on account of the difficulty in finding refractory material which will stand the intense heat. Firebrick of the best quality is rapidly melted, and it is probable that boiler plates unprotected by firebrick would not last long in the hottest part of the furnace.

In the case of liquid fuels, such as petroleum, a similar intimate mixture with the air can be attained, and the relative quantity of each regulated. The apparatus now invariably used is some form of injector, by means of which, through the agency of a jet of steam or compressed air, the fuel and air are introduced into the furnace. One of the most successful applications to locomotives is that made by Mr. Urquhart, the engineer of the Griasi and Tsaritsin railway, in south-eastern Russia. The Figs. 29 and 30 illustrate his method. The injector is of the ordinary circular type, impelling a solid jet of steam and petroleum refuse, surrounded by a current of air, through a tube traversing the water space at the bottom of the fire-box. To keep up the temperature of the flame, during combustion, the oil is thrown into a brick oven, built upon the ash-pan, and from thence it is distributed, by numerous openings, into the fire-box, where the chemical reaction is

completed, and the heat afterwards absorbed by the boiler tubes. The brickwork also serves as a store of heat

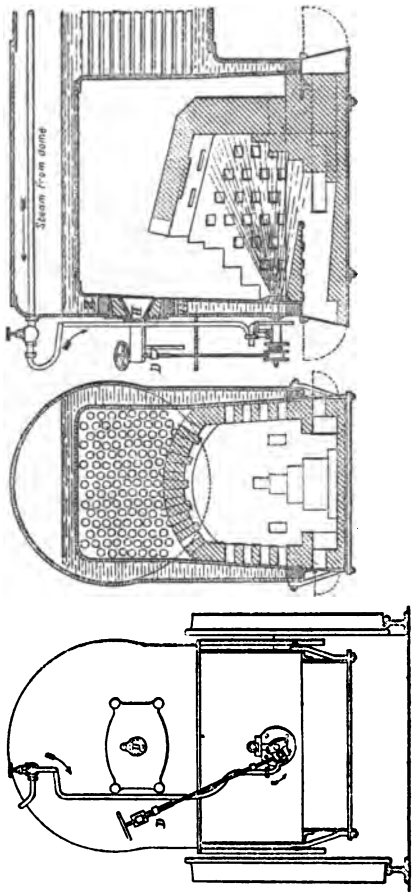


FIG. 29.

available for relighting the oil when the jet has to be stopped at stations or on a falling gradient.

On the Volga, and the Caspian Sea, petroleum refuse has now almost superseded all other fuel in marine boilers. One of the forms of apparatus in use is illustrated in Fig. 31. The injector, in this case, delivers a hollow cone of oil. Air is introduced both inside and outside the jet, so that the mixture is still more intimate than in the arrangement adopted by Mr. Urquhart. The apparatus is placed in the centre of the sliding furnace doors, and is suspended

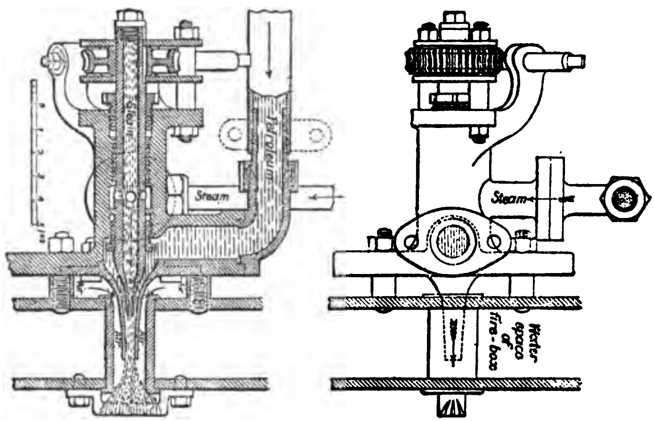


FIG. 30.

by a pair of swivel joints from the ceiling of the stoke-hole, so that it can swing back for the purpose of cleaning or repairs, and the doors can be opened to give access to the furnace. Petroleum refuse is supplied through the right-hand swivel joint from a service tank placed a little above the boilers, while steam is admitted through the left-hand swivel. The furnaces are not always lined with fire-bricks, but from what has already been said, it is obvious that a lining would tend very much to promote complete combustion, and would at the same time protect the boiler

plates from the intense heat engendered in the immediate vicinity of the flame as it is first formed.

The economy arising from the use of petroleum is not

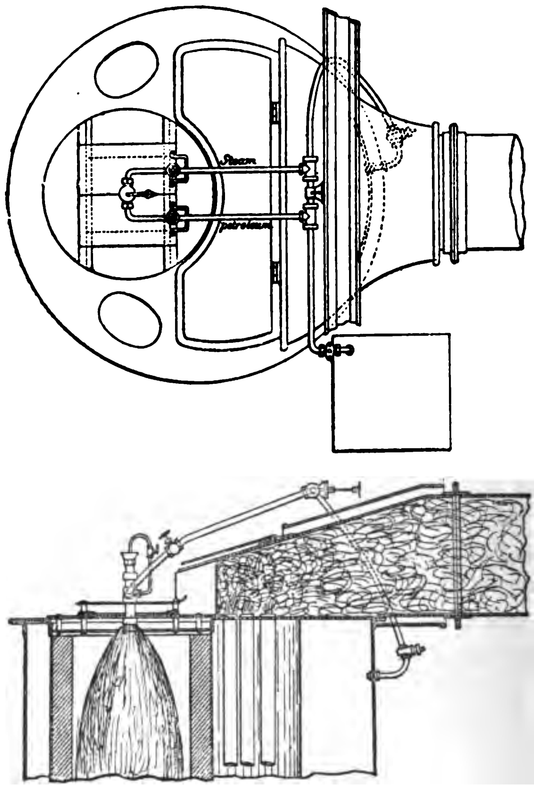


FIG. 31.

alone due to its high calorific power, which is nearly fifty per cent. greater than that of the best coal, but also to the facility with which it is stored, placed on board the steamer or locomotive, and the economy of labour in firing and

trimming. At the railway stations and on the wharves where steamers take in fuel, large iron covered tanks are placed; these are filled from petroleum waggons or barges which bring the material in bulk from the oil wells. The oil is run into the tenders or bunkers by means of pipes terminating in flexible hoses. The saving of time and the avoidance of noise and dust, especially in the case of passenger steamers, is in itself a very great advantage.

A still finer subdivision of particles is attained when the fuel is made to assume the gaseous form before combustion sets in. We have a splendid illustration of this method in the Siemens regenerative gas furnace. According to this system, a crude gas is manufactured in a species of oven called a "producer" (Fig. 32), which consists of a kind of oven A, rectangular in plan, fitted at the bottom with firegrates B arranged over water ash pans C. Coal is supplied by the hopper D, a jet of steam enters by the pipe E, and the gases produced escape by the opening F and the pipe G to the gas main H. The producer is generally sunk in the ground in order to facilitate the flow of the gas, which being lighter than air, naturally tends to rise towards the furnace which it is intended to supply. The spaces I are merely passages from which the firegrates are attended to. A considerable depth of fuel is kept on the bars. The layer, in immediate contact with the air entering between the bars, burns to carbonic acid, and the energy of this reaction raises the temperature of the carbon in the mass of the fuel to a red heat, at which the carbon acid formed beneath it is decomposed by taking up an additional equivalent of carbon, and carbonic oxide gas flows up into the producer. The heat of the lower layer of fuel causes the hydro-carbon gases in the upper to distil, and also decomposes the vapour of water arising

from the ash pans and from the steam jet, thus liberating hydrogen so that a mixture of various inflammable gases and nitrogen becomes available for use. It is obvious that the supply of fuel must be so regulated that no air undeprived of its oxygen may pass right through, else combustion would take place in the producer, or an explosive mixture would be formed. The gases rise into

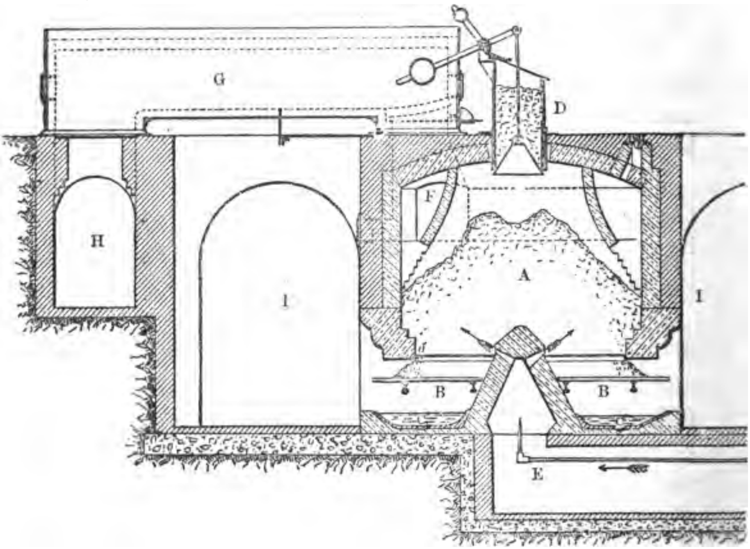


FIG. 32.

the furnace, which they enter, accompanied by the proper quantity of air, and unite with it, much as we see in an ordinary Bunsen burner. It is evident that the intimacy with which the gas and the air may be made to mix, the relative proportion of each, and total rate of combustion, must be capable of the most exact control.

There is one method by which the combustion of solid

fuel on ordinary grates may be ameliorated, and that is by the use of forced draught. The feeble pressure obtainable from an ordinary chimney necessitates thin and loose layers of fuel, but when air can be blown in, the layers may be increased in depth, and made more compact, so that the air is brought into more intimate contact with the combustible. By this means the quantity of air may be reduced to the theoretical amount, and the temperature of the furnace exalted in proportion.

Little or nothing has been done to investigate the specific heat of gases at high temperatures, so that the uncertainty of calculations depending on an accurate knowledge of this property must still remain.

The investigations of St. Claire-Deville have revealed that, at high temperatures, compound gases become resolved into their elements, and that chemical combinations cease to take place. This phenomenon is called "Dissociation."

According to laboratory experiments, water and carbonic acid commence to dissociate at about 2,500° Fahr. absolute, and this action has an important bearing upon the temperature which a furnace is capable of attaining, although it evidently does not fix any exact limit, because it is certain that wrought iron and platinum can be melted in a coal fire, although the fusing points of these metals is about 3,500° absolute. We shall probably not be far wrong if we assume 4,000° absolute to be the superior limit of temperature of any furnace, a limit which, if the theory of dissociation be correct, can never be surpassed. The invention of a trustworthy pyrometer will alone be able to yield more definite information on this subject.

We may assume that the specific heat of coal, and of the products of combustion at constant pressure, are the same as that of air, namely, ·238, and it is highly pro-

bable that by the use of forced draught, of properly constructed grates, or of powdered, liquid or gaseous fuel, it may be possible to ensure perfect combustion with only the quantity of air required to supply the exact weight of oxygen necessary to combine with the elements of the fuel. Under such circumstances, it is not difficult to calculate the temperature of the furnace when we know how many units of heat a pound of the fuel is capable of yielding, for it is only necessary to divide that value by the product of the weight of fuel and air into the specific heat, and add the quotient to the temperature of the air. Hence—

$$\text{Rise of temperature} = \frac{\text{Units of heat.}}{\text{weight of complete fuel} \times \cdot 238}$$

Take the case of Durham coke, for example. From the table of the calorific value of fuel, page 99, it will be seen that one pound of coke is capable of yielding 13,640 units of heat, therefore:

$$\text{Rise of temperature} = \frac{13{,}640^{u}}{(1+11\cdot 5)\ \text{lbs.} \times \cdot 238} = 4{,}588^\circ$$

and here we are at once met by a consideration which too often escapes notice, namely, the effect of the pressure of the atmosphere under which we live on all the operations which we perform. The effect of combustion is to convert solid fuel into an immensely greater volume of gas; 1 lb. of Newport steam coal, for example, when burned with the least possible air, produces 147 cubic feet of various gases at 32° Fahr., or 492° absolute. If the temperature of the furnace rises from 50°, or 510° absolute to 5,376° absolute, the volume will be increased in the proportion of the absolute temperatures, or as $\frac{5376^\circ}{492^\circ}$ or a little

more than eleven-fold, so that each pound of coal will yield 1,606 cubic feet, and in order to make room for this volume, the atmosphere must be moved aside at the cost of work = 1,606 cubic feet × 144 sq. in. × 14·7 lbs. = 3,400,100 foot-pounds, equal to the conversion of 4,404 units of heat, or 30 per cent. of the whole heat of combustion. If the action could be carried on in vacuo, there would be no appropriation of heat to the work of displacing the air, and then the temperature of the furnace would be much higher, namely, in the case of Newport steam coal, it would rise from 5,376° absolute to 7,362° absolute, an increase of 36 per cent. The coefficient for the specific heat of gases which we have employed allows, as will be remembered, for this external work done during expansion.

In any practical applications of fuel, we cannot arrange for the products of combustion to escape at a lower temperature than that of the surrounding air, and generally the temperature is much higher. Assume, as an extreme case, that the products of combustion have fallen to 50°, or 510° absolute, the gases will have shrunk to

$$\frac{147 \text{ c. ft.} \times 510^\circ}{492^\circ} = 152 \text{ cubic feet,}$$

and the work done in displacing the atmosphere will be 152 c. ft. × 144 sq. in. × 14·7 lbs. = 322,500 foot-pounds, corresponding to 418 units of heat, or nearly 3 per cent. of the total heat of combustion. The work expended in displacing the air in the furnace is restored again as the gases cool, but the final loss, just calculated, is complete and irrevocable.

What, then, is the limit of efficiency in the combustion of fuel?

We must apply Carnot's theory, and assuming that 4,000° absolute is the maximum temperature to which we can attain, and 510° absolute is the lowest, we have—

$$\frac{4000^\circ - 510^\circ}{4000^\circ} = \cdot 872$$

that is to say, under the exceptionally favourable circumstances assumed, there must be a loss of 13 per cent. It may not, at first sight, be very apparent why the high temperature of the furnace should increase the efficiency when the smoke escapes at the same temperature in either case, and the same quantity of heat is yielded by combustion, but the explanation is simple. The cause of the reduction of the temperature of a furnace is the introduction of an excess of air. This air passes out by the chimney, and carries off heat in proportion to its weight; hence, in all cases where it is desired to attain the highest efficiency in the use of fuel, the aim must be to use as little air as possible, so as to raise the temperature of the furnace to the utmost, and to cool down the smoke usefully as much as possible.

Under ordinary circumstances, at present at least, 50 per cent. excess of air is admitted into furnaces, and the chimney temperature rarely falls below 400°; this reacts unfavourably on the duty of fuel at both ends of the operation. Supposing 16·5 lbs. of air admitted to Newport steam coal, the rise of temperature of the furnace would be reduced to—

$$\frac{14143^\circ}{17\cdot 5 \times \cdot 238} = 3396^\circ$$

the absolute temperature would therefore be

$$3396^\circ + 510^\circ = 3906^\circ$$

and the smoke being at 860° absolute, the efficiency will be $\frac{3906^\circ - 860^\circ}{3906^\circ} = \cdot 78$, or 78 per cent., and the water evaporated would be 14·64 lbs. × ·78 = 11·42 lbs. per pound of coal from and at 212°, which is very nearly the duty to which a good boiler can attain.

According to Carnot's doctrine, the temperature of the products of combustion should be reduced as low as possible, in order to attain the most economical results. In steam boilers it is possible, and practicable, to reduce the temperature to very little above the temperature of the feed-water supplied, because it is more economical to produce the necessary draught by means of a blower than by means of a hot chimney. From experiments made by the Admiralty, it appears, that a pressure of air equal to a column of water 1″ high produces a very strong draught—much greater than that due to a chimney fitted with a steam blast. We have seen that one pound of coal requires practically 18 lbs. of air to consume it; the volume of this at 510° = 231 cubic feet, and a pressure of 1″ of water represents 5·2 lbs. per square foot, hence the work done in forcing in the air will be 231 × 5·2 = 1,200 foot-pounds. Suppose we have a blower, driven by a small engine consuming 5 lbs. of coal per indicated horse-power per hour, and suppose the blower does only 50 per cent. duty, we should have 2,400 indicated foot-pounds, and if this be done in a minute, then the units of heat absorbed by the engine would be :—

$$\frac{5 \text{ lbs.} \times 14{,}143\,u \times 2{,}400 \text{ foot-pounds}}{60 \text{ min.} \times 33{,}000 \text{ foot-pounds}} = 88\,u$$

If the boiler had depended on chimney-draught, the temperature of the smoke must have been at least 400°,

and the loss of heat = 19 lbs. × ·238 × 350° = 1,582u, or eighteen times as much as the blower would consume. But suppose that, by the use of forced blast, we were able to arrange a feed-heater, so as to reduce the temperature of the chimney to 100°, or only 50° above that of the cold water fed in, then the heat saved per pound of coal would be 19 lbs. × ·238 × 300° = 1,356 units, more than fifteen times the heat absorbed by the blower, and competent to raise the 10 lbs. of water fed in per 1 lb. of coal 135·6°, or to 185·6°, a temperature still far short of that of the boiler. Two things are apparent from this consideration—namely, first that a decided economy will arise from blowing air into boilers by engine-power, instead of drawing it in by means of a chimney; and secondly, that the feed water-heater should be detached from the boiler, and made to do its work at the lowest temperature practicable.

In furnaces used in the various arts, such as in metallurgy, in glass, and chemical manufactures, it is, generally, impossible directly to reduce the temperature of the smoke to economical limits. In blast furnaces, the intense heat at the boshes is, in a great measure, taken up by the mass of fresh materials continually being added at the top, but in most cases, especially where steam is not required, the regenerative system has to be adopted.

The regenerator appears to have been invented in the early part of this century, by Stirling, for his hot-air engine. The principle is this: The hot body ejected from the heat-engine passes through a vessel filled with metal plates, bricks, or any other substances presenting a large surface of contact, and being good absorbers of heat. The consequence is, that one end of the regenerator, that nearest the engine, becomes highly heated, while the opposite end is comparatively cool. After a time the flow is reversed,

and a cold current, which it is desired to heat, sets in towards the engine, and takes up the heat which the flow in the opposite direction had left in the regenerator.

The late Sir William Siemens adapted this system to furnaces working at high temperatures. Fig. 33 represents

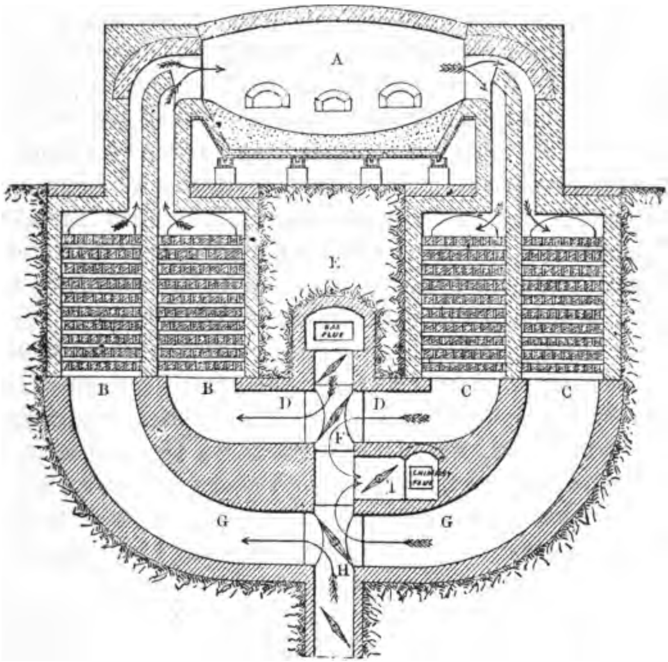


FIG. 33.

his Regenerative Furnace. A is the hearth, B B and C C are the regenerators, consisting of chambers filled with firebrick laid in reticulated fashion so as to afford sufficient area for the passage of the air and gas. D D are gas flues proceeding from the gas main E, and controlled by the two

way valve F, by means of which the current of gas can be turned at pleasure either to the right or left. G G are flues connected with the external atmosphere, and the current of air is controlled by the two way valve H. I is a flue leading to a chimney. The furnace is started by lighting a fire of wood on the hearth and allowing the gas and the air to flow in through their respective regenerators B B, while the products of combustion are drawn out by the chimney draught through the regenerators C C. This process goes on for a couple of hours, till the upper portion of the brickwork in the regenerators C C is thoroughly heated, the valves F and H are then turned over, the gas and air stream in through regenerators C C, while the products of combustion pass out by regenerators B B. In another two hours the valves are again turned over, and the process goes on, in a similar manner, indefinitely. The chambers are made so deep that the maximum heat of the bricks extends a good way below the surface, and the duration of the flow of air and gas is so regulated that the layers of bricks nearest the furnace are not appreciably cooled, so that the temperature of the air and gas entering the furnace is practically constant. One end, therefore, of the regenerator is always at a constant high temperature, and the opposite end at a constant low one, the maximum heat of the space between oscillating up and down, according as the cold current or the hot is passing through. It will be readily understood that such an arrangement must lead to a continual increase of heat in the furnace each time the current of air and gas is reversed. Imagine the furnace started for the first time. The air and gas would come up to the point of combustion cold, they would be increased in temperature by the heat due to the chemical reaction, and would communicate the surplus heat to one

pair of regenerators, B. On reversing the valves, the fuel would enter the furnace at a high temperature, the heat corresponding to the energy of combustion would be added to this, the flame would be hotter, and regenerator C would be more highly heated than B. On again reversing, the fuel would reach the hearth still hotter than at the previous turn, and the temperature of the flame would be again increased. A repetition of this process would lead to temperatures which no material, however refractory, could stand; but here dissociation steps in and puts a salutary limit to the temperature which can be attained, a limit which we have assumed to be about 4,000° Fahr. absolute.

The effect of the regenerators on the duty of the furnace is easily calculated. The temperature of the products of combustion leaving the regenerator is reduced to about 250° Fahr. or 710° absolute, and this fall has taken place in heating up the air and gases entering the furnace, and therefore, in doing useful external work; hence, we must consider the furnace and the regenerator as an engine working between our assumed maximum of 4,000° absolute and a minimum of 710°; consequently, the duty to be expected from the fuel will be $\frac{4,000° - 710°}{4,000} = \cdot 82$.

Without the regenerator, the product would have escaped at a bright red heat, at least, 1,500° or 1,960° absolute, and the duty would have been $\frac{4,000° - 1,960°}{4,000} = \cdot 51$; hence, the regenerators secure an economy of 31 per cent.

In a recent paper read at the Iron and Steel Institute, Mr. Siemens stated that careful experiments with an ordinary reheating furnace, using solid fuel, and a regenerative gas furnace, shewed an economy of $33\frac{1}{3}$ per cent.,

which approaches very closely to the result deduced from our purely theoretical considerations.

The regenerative principle is capable of application wherever the products of combustion are not reduced directly to a very low temperature, as they may be, for example, in steam boilers. Thus, the waste heat of a Crampton furnace has been utilised in heating the air and fuel before it enters the furnace, and in raising steam, while Mr. Urquhart has applied the principle partially to warming some of the air as it enters the firebox. In his arrangement, only a portion of the air required for combustion enters with the jet of petroleum, the rest is admitted through passages made in the lower part of the brick oven, through apertures in the ash-pan; the heat, which would otherwise produce very little effect on the boiler, is thus made profitable use of in heating the air required for combustion.

CHAPTER V.

In the latter part of the last chapter it was shown how the waste of heat in furnaces, in which the work has to be done at a high temperature, is prevented by the Siemens Regenerator. The same principle can be further illustrated by a still more interesting case, connected with the blast furnace for smelting iron ore.

A modern blast furnace consists of a hollow tower, with thick walls, hooped with iron, having the inside shaped principally in the form of two truncated cones, the upper cone having its smallest diameter at the top, or throat, of the furnace, and the lower one having its least diameter at the bottom, where it joins a smaller cylindrical part, or hearth, provided for holding the liquid iron. The top, or throat, of the furnace is fitted with a large iron hopper, by means of which the fuel and ore are introduced. In all the best furnaces this hopper is closed by an iron cone, having its apex turned upwards, and capable of being lowered sufficiently to allow any materials in the hopper to drop into the furnace. Some of the modern furnaces attain to immense proportions, viz. 90 feet high, and 29 feet diameter inside, at the largest part, with a capacity of 33,400 cubic feet. Many furnaces are not more than 60 feet high, and are even lower in districts where the coke used is of a soft character, or where coal is employed.

By means of the hopper, the proper proportions of fuel, ironstone, and limestone are continually supplied, the furnace being always kept nearly full night and day. The blast of hot air is forced in by means of tuyeres introduced through the sides of the upper part of the hearth. The pressure varies greatly, being least when charcoal is used as the fuel, and greatest with hard coke, or anthracite. The general pressure in this country is from 4 lbs. to 6 lbs. per square inch, but $10\frac{1}{4}$ lbs. is being used in America in certain works, where as much as 1,833 tons of iron per week are produced from a single furnace, with the aid of "Cowper stoves." The action in the furnace is as follows:—The hot air, forced in at the hearth, enters immediately into intense combustion, with a corresponding quantity of carbon, thus producing carbonic acid gas and sufficient heat to melt the iron ore, which had been previously reduced in the upper part of the furnace, and also the limestone, which acts as a flux, so that both drop down into the hearth, the liquid iron sinking through the liquid slag formed of the limestone and refuse of the iron ore; the slag runs out continuously at a small hole at the side above the liquid iron, which is only tapped at intervals. The carbonic acid gas, in its upward course through the red-hot materials which are slowly making their way down, takes up another equivalent of carbon, thus becoming carbonic oxide, which, at a red heat, reacts on the oxide of iron of the ore, and reduces it to a metallic sponge, the oxygen uniting with the carbon in the carbonic oxide, converting it again into carbonic acid, which, however, is again reduced by coming into contact with carbon from the fresh fuel.

The process goes on for a considerable portion of the height of the furnace, the temperature becoming lower and

lower, on account of the fresh cold materials continually added, until it gets too low for chemical reaction to proceed. The gases escaping ultimately are, therefore, chiefly carbonic oxide and the nitrogen of the air which was forced in at the hearth. In olden times, these gases were allowed to escape freely at the top of the furnace, which was always open, and when using coal in the "Black Country," they burned with a bright flame, producing a conspicuous feature in the landscape.

After the introduction of hot blast, however, the escaping gases were collected and carried down, by means of pipes, to heat the air entering the bottom of the furnace. A marked economy of fuel, and an increase of yield, followed this grand improvement; but a limit to the temperature of the blast was soon reached from the want of some material to stand the intense heat of the air-heating stoves. Cast-iron pipes in various forms, set in brick ovens, were used; the wear was very great, and the leakage from defective joints so serious, that high pressure blast could not be employed, nor the temperature of melting lead, about 600°, exceeded.

Here Mr. E. A. Cowper stepped in, and applied the regenerative principle to blast-heating stoves. (Fig. 34.) These have now assumed grand proportions, 60 feet high and 25 feet diameter.

The stoves are worked in pairs, one stove of a pair being heated by the combustion of the gases brought down from the furnace top, and the other imparting the heat previously acquired to the blast. Each stove consists of an air-tight wrought-iron cylindrical casing, lined with firebricks. Towards one side a flame-flue A is carried up, while all the rest of the cylinder is filled with firebrick, formed in short lengths, and built up so as to make a honeycomb arrange-

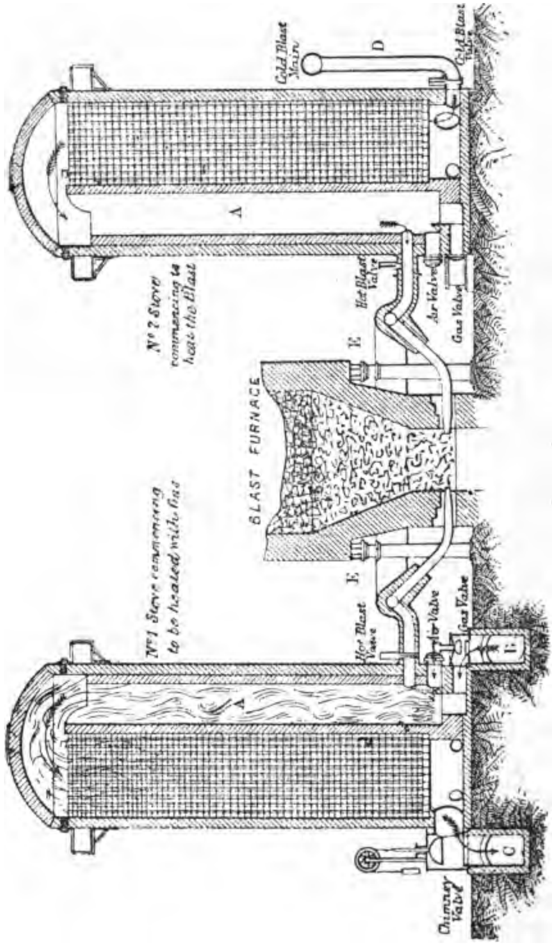


FIG. 31

ment with walls about 2 inches thick. Each cell is continuous from top to bottom, but stops short of both, so that there is a chamber at the top, into which the flame-

flue opens, and one at the bottom, connected with the chimney and the blast main. The action is as follows:—Taking first the left-hand stove, the gases are conveyed from the furnace by the flue B, and are admitted, by a suitable valve, to the bottom of the flame-flue A, and a supply of air, also controlled by a valve, is arranged to mix as intimately as possible with the gases. Complete and very intense combustion takes place in the flame-flue, and the highly heated products having ascended to the top, pass down the honeycomb regenerator to the chamber in the bottom, and so through a suitable valve to the chimney flue C. The heating of the stove goes on for several hours, until the full temperature has been obtained to a sufficient depth in the regenerator; that is to say, to near the bottom. The gas, air, and chimney valves are then closed and the condition illustrated in the right-hand stove is reached, the valve on the blast main D is opened, and the cold air admitted into the chamber under the regenerator; the air rises through the colder part first, then becomes fully heated, and passes through the remainder of the regenerator without taking up more heat, and after reaching the top, turns down the flame-flue A, and so passes through a valve to the tuyere E, by which it is injected into the base of the furnace. As the stove heats the air the brickwork cools gradually from the bottom upwards, the upper layers changing very little in temperature, and when, after several hours, the cold zone has risen so high as to affect the temperature of the blast, the air is shut off, and the gas again turned on. In the meantime, the fellow-stove has been acting in the reverse direction, so that one stove is always heating the blast, and the other is being heated by the gas. The effect of this ingenious and simple invention is, that the blast can be heated to 1,600°, and the

products of combustion can be cooled to from 250° to 350°, without leakage, and with scarcely any wear and tear.

It was stated that the blast furnace is a particularly interesting case; the reason being, because the products of combustion are endowed with energy, partly in the form of heat, and partly in the potential state of carbonic oxide gas; so that if this gas were allowed to escape, even in a comparatively cool condition, a great waste of heat would take place.

The work due to the energy of combustion in the bottom of the furnace is expended partly in heating the cold materials charged into the furnace, partly in decomposing the limestone, and partly in detaching the oxygen from the ore. These operations reduce the temperature of the gases, in a well-conducted furnace, to as low as 374°, so that, at first sight, no great loss occurs; but if we analyse the gases, we find that associated with 12·1 per cent. of carbonic acid and 59 per cent. of nitrogen, are 26·1 per cent. of carbonic oxide and 2·51 per cent. of hydrogen. It has been found by experiment that one pound of carbonic oxide burned to carbonic acid develops 4,326 units of heat; and one pound of hydrogen converted into vapour, 53,338 units, so that the combustion of the mixed gases will develop

$$
\begin{array}{lrl}
CO & \cdot 261 \times 4{,}326 = & 1{,}129 \text{ units.} \\
H & \cdot 0281 \times 53{,}338 = & 1{,}499 \text{ units.} \\
\hline
 & \text{Total} \quad . \quad . & 2{,}628 \text{ units.}
\end{array}
$$

These reactions require ·3738 lb. of oxygen for their completion, corresponding to 1·714 lbs. of air. Supposing the gases to burn at the top of the furnace with the theoretical quantity of air only, the temperature would

rise $\frac{2,628}{2\cdot714 \times \cdot238} = 4,068°$, so that by letting the gases escape, even cold, a very great loss would be experienced. It is possible, however, in consequence of the large proportion of neutral gases, amounting to 71 per cent., that a considerable excess of air is necessary to ensure complete combustion of the carbonic oxide and hydrogen, especially as the burners in the stoves do not mix the gases very perfectly. If we suppose that twice the quantity of air is necessary, then the temperature of flame will only rise $\frac{2,628}{4\cdot428 \times \cdot238} = 2,522°$; and supposing the air at 50° and the gases at 400° the mixture of air and gas entering the stove will be at 129°; then the temperature of the flame will be 2,651°, equal to 3,111° absolute, a temperature at which cast steel will melt.

Bearing in mind Carnot's law, that the efficiency of a heat engine depends only upon the range of temperature, and is quite independent of what takes place during the working, provided always that the fall of temperature is caused by the work done, and Berthelot's law that intermediate reactions do not affect the final thermal results, we can compare the efficiency of various furnaces if we only know their extreme temperatures. Unfortunately, we have no means of measuring the temperature of the blast furnace where the heat is most intense; we must estimate it, therefore, by supposing that the rise of temperature is that due to the combustion of coke with the minimum amount of air, that is 4,588°; but this exceeds the limits we have set, due to dissociation, which is 4000° absolute; let us then assume that as the maximum. Take, first, the open-topped furnace, in which the gases are not utilised, but burn at 2,460° absolute, the air blast would be at about

800°; the absolute temperature of the hottest part will be 4,000°, therefore the efficiency will be—

$$\frac{4,000 - 2,460}{4,000} = \cdot 38, \text{ or only 38 per cent.}$$

Next, take a blast furnace, using pipe stoves, from which the products of combustion go to the chimney at an ascertained temperature of 1,250°, or 1,710° absolute, and with the same temperature of blast as before, the efficient is $= \frac{4,000° - 1,710°}{4,000} = \cdot 57$, or 57 per cent., a gain of 19 per cent.; and, lastly, take the furnace with Cowper stoves, heating the blast to 1,600°, and allowing the product of combustion from the gases to escape to the chimney at 760° absolute, we have the temperature of the furnace at 4,000° as before, but the smoke escapes from the stoves at only 760° absolute.

$$\text{The efficiency} = \frac{4,000° - 760°}{4,000} = \cdot 81.$$

The Cowper stove, therefore, realises a saving of ·81 — ·38 = 43 per cent. over the open-topped furnace, and ·81 — ·57 = 24 per cent. over the pipe-stove furnace. Mr. Cowper states that, on the average of 100 furnaces, the saving in practice is 20 per cent. in fuel, which agrees fairly well with the estimate we have made, based upon the truth of the general principles which have been explained.

The work done by the energy of combustion in a blast furnace is so intricate, and requires considerations so *purely* chemical, that they cannot suitably be discussed here; it will be sufficient to state that the effect of the Cowper stoves on the blast furnace is to make from 10 to 20 per cent. more iron, with a saving of coke ranging from

4 to 5 cwt. per ton of iron made, an advantage due to the improved chemical action, consequent upon the high temperature of the blast.

If it were possible to reduce the products of combustion in the stoves to the temperature of the atmosphere, say 50°, the duty would increase to 87 per cent., and beyond that it will be impossible to increase the economy of a furnace. The temperature of the blast being considerably above red heat, it cannot be measured by an ordinary thermometer. The instrument used is a pyrometer, constructed on the principles explained in Chapter II., page 59; but a short hollow cylinder of copper is used instead of a platinum ball, and the mercury thermometer in the water space is fitted with a sliding scale, the zero of which can be set to the end of the column of mercury, wherever it may be. The scale is graduated by experiment, so that the temperature attained by the ring can be read off at once. The pyrometer was first described by Mr. Wilson, of the Bridgewater Works, St. Helen's, in 1852. The instrument has been manufactured by Messrs. Siemens and Co., hence it is commonly, though erroneously, known as the Siemens pyrometer.

Mr. Cowper successfully exhibits the principle of his stoves by means of a working model. An earthenware cylinder filled with fragments of firebrick is supported over a large Bunsen burner, the flames make their way through the interstices between the brickbats and raise them to a red heat which gradually travels upwards. It takes several hours before the products of combustion escaping from the top are hot enough to char the paper chimney used to create a draught; as soon as this is the case the stove is removed from its stand, and set on a pad of clay. The top is closed by means of a zinc plate luted

down with clay and secured by a weight. A blast of cold air is then made to flow from the top downwards, and issues by a side opening near the bottom, so highly heated that it easily melts strips of lead held in the current, and sets fire to a twist of paper the moment it is brought within its influence.

The simplest machine in use for the conversion of heat into work is a gun. It is a single-acting engine which completes its work in one stroke, and does not, like most engines, work in a continuous series of cycles. In the discharge of artillery many interesting considerations arise.

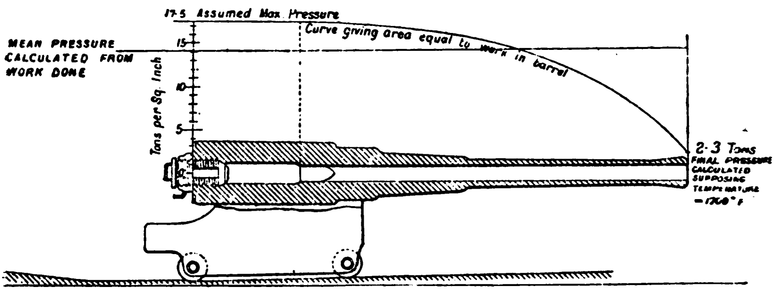


FIG. 35.

It will probably be best to illustrate the subject from the first, by taking the case of the new pattern 10-inch breech-loading rifled gun. This weapon weighs 27 tons, is 26 feet 8 inches long, and discharges a shot weighing 500 lbs., impelled by the energy latent in 300 lbs. of gunpowder, with a muzzle velocity of 2,100 feet per second, the shot, at the same time, receiving a rotatory motion of 84 revolutions per second.

From the experiments of Sir Frederick Abel and Captain Noble, we know that the maximum temperature of the explosion of pebble powder is 4,420° Fahr. absolute. The

temperature of the gases issuing from the muzzle of the gun has not been measured, but it certainly attains to a bright red heat, which is about 2,160° absolute. The powder, therefore, works between the temperatures of 4,420° and 2,160°; the duty which we may expect will consequently be, according to Carnot's law—

$$\text{Duty} = \frac{4{,}420 - 2{,}160}{4{,}420} = \cdot 5113$$

that is to say, we must not expect to realise more than 51 per cent. of heat developed in the combustion of powder.

From the authority already quoted, we learn that the explosion of a pound of powder develops 1,300 units of heat. The specific heat is given as ·183 at constant volume, hence the total heat from absolute zero resident in exploded powder, at an atmospheric temperature of 50°, or 510° absolute, is—

$$510° \times \cdot 183 + 1{,}300 = 1{,}393 \cdot 3 \text{ units,}$$

and of this we can only expect to realise—

$$1{,}393 \cdot 3 \times \cdot 5113 = 712 \cdot 41 \text{ units,}$$

corresponding to $\dfrac{712 \cdot 41 \times 772}{2{,}240 \text{ lbs.}} = 245 \cdot 53$ foot-tons of energy per pound of powder, so that the total charge of 300 lbs. should be capable of producing work amounting to 73,658 foot-tons.

The work done by the discharge of the gun must be classed under two heads:—

I. Work external to the gun, the reaction of which causes recoil; and

II. Work self-contained in the gun, which produces no visible effect upon it.

To the first class belong—

1. The energy imparted to the shot in its forward motion.

2. The energy absorbed in the expulsion of the powder gases.

3. The work done in displacing the atmosphere by the ejection of the shot and powder gases.

To the second class belong—

4. The energy expended in producing rotation in the shot.

5. The work done in overcoming the friction of the gas check.

6. The work done in stretching the material of the gun, in setting up vibratory motions, and in compressing the shot and breech-block.

7. The friction of the powder gases against the bore of the gun.

8. The energy absorbed in heating the gun.

We will deal with these items in detail.

1. The muzzle velocity of the shot can be determined with great accuracy by experiment, and, in the particular gun we are considering, has been found to be 2,100 feet per second; consequently the energy imparted to the

$$\text{Shot} = \frac{500 \text{ lbs.} \times 2{,}100^2 \text{ ft.}}{64 \cdot 4 \times 2{,}240 \text{ lbs.}} = 15{,}285 \text{ foot-tons.}$$

2. The combustion of gunpowder results in about 57 per cent. of very finely divided solid matter, and 43 per cent. of permanent gases. That the solid matter *is* in a very fine state of subdivision may be inferred from the slowness with which powder smoke falls to the ground. When large guns are fired at sea, and heavy clouds of smoke are formed, they sail over the water for many

miles, and remain visible for a long time; though fired within a few feet of the sea level. This is due to the viscosity of the air. The researches of Sir W. Thomson, of Poiseuille, Graham, O. E. Meyer, Helmholtz, Stokes and Clerk Maxwell, have determined the laws which govern this property of matter. The rate at which a particle will fall through a viscous substance is directly as the difference of density between the particle and the substance, directly as the square of its diameter, inversely as the absolute temperature and independent of pressure; hence it is obvious that the decrease in the diameter of a particle will cause a very rapid decrease in its rate of falling. It is easy to satisfy oneself of this truth, by mixing up a little ordinary mud with water. It will then be seen that the coarser particles soon fall to the bottom, the smaller ones follow gradually in the order of their linear dimensions, but there will remain a residuum of very fine particles, which take days, and even weeks, to settle down completely. Some waters, notably those of the Nile, are impregnated with particles so minute that they cannot be separated by filtration through sand or filter paper, nor will they subside in any definite time.

In the atmosphere, again, particles of moisture, smoke, or dust, subside in the same manner at varying rates. Professor Tyndall found, in his beautiful experiments instituted to overthrow the doctrine of spontaneous generation, that it required three days for all the dust to settle down in a box 14 inches long by 14 inches high and 8½ inches deep, so as to become what he called "optically empty"—that is to say, that a vivid ray of light should pass through without revealing its track. When the impurities are so thick that they sensibly alter the specific gravity of the gas, then the whole mass moves together;

this phenomenon may be seen in fogs and thick cold smoke, which will lie in hollows and pour down valleys like water, and present a level upper surface.

The condition within the bore of the gun is not indeed the same, because the smoke formed is the result of chemical action after the gases have left the gun; but the particles of solid matter in the bore are certainly not larger than those which form the smoke, and though they constitute 57 per cent. of the cloud, they do not sensibly alter its gaseous properties; and, therefore, the mixture of solids and gases, forming the products of combustion of powder, may be treated, as far as its physical properties are concerned, as all gaseous, but of a higher specific gravity than the pure gases evolved. At the moment of the shot leaving the muzzle, it has been ascertained by experiment, though not in a trustworthy manner, that the gas pressure is about 3·875 tons, or 8680 lbs., per square inch; the volume of the bore of the gun is 16·72 cubic feet; hence the 300 lbs. weight of powder gas occupying that volume must weigh 17·94 lbs. per cubic foot; consequently, the pressure will be represented by a column of gas, of the above density,

$$= \frac{144 \text{ sq. in.} \times 8{,}680 \text{ lbs.}}{17 \cdot 94 \text{ lbs.}} = 65{,}013 \text{ feet high.}$$

When the muzzle of the gun is suddenly opened, the gases will begin to issue as from an orifice in the side of a vessel, with a velocity proportional to the height of the gaseous column $= 8 \cdot 05 \sqrt{65{,}013} = 2{,}125$ feet per second, or very little more than that of the shot, which seems to indicate that the 10-inch gun cannot, with advantage, be increased in length without increasing the charge of powder. Supposing the whole body of gas to issue with

the above velocity, then the energy expended will be $\frac{300 \text{ lbs.} \times 2{,}125^2}{2{,}240 \text{ lbs.} \times 64 \cdot 4 \text{ feet}} = 9{,}388$ foot-tons. But the gases being elastic, their whole body will not move at the same speed, so that the above calculation may be erroneous to a considerable extent. The limits between which the energy absorbed in the expulsion of the powder gases will vary may be determined by the following considerations. One pound of powder produces 4·485 cubic feet of gas at the freezing point, and under the pressure of one atmosphere. This volume would be increased to 4·651 cubic feet at a temperature of 50°, consequently 300 lbs. of powder would yield 1,395 cubic feet of gas at atmospheric pressure and temperature. We must suppose that this gas will obey the laws applicable to all permanent gases. Its specific weight is nearly three times that of air, hence the work done in heating at constant pressure will be less; the value of γ consequently is only 1·143 if the specific heat at constant volume is taken as ·183. Suppose the gases violently compressed into the bore of the gun, measuring $16\frac{1}{2}$ cubic feet, the pressure would arise according to the ordinates of an adiabatic curve, and we should have, finally, $p = \frac{14 \cdot 7}{2{,}240}\left(\frac{1{,}395}{16 \cdot 72}\right)^{1.143} = 1 \cdot 03$ tons pressure per square inch in the gun, and a temperature of

$t = 510°\left(\frac{1{,}395}{16 \cdot 72}\right)^{1.143} = 960°$ absolute. The work done in compressing the gas would be—

$$W = \frac{1{,}395 \text{ c. ft.} \times 2{,}117 \text{ lbs.}}{\cdot 143 \times 2{,}240}\left\{1 - \left(\frac{1{,}395}{16 \cdot 72}\right)^{\cdot 143}\right\} = 8{,}131$$

foot-tons. Now the compressed gas, if suffered to expand suddenly, would do the same work, and the reaction

on the gun, according to Newton's third law, would be the same. This would mark the superior limit of work done in expelling the gases. If, on the other hand, the gases were compressed slowly into the gun without change of temperature, the pressure would rise along the ordinates of an isothermal curve, and would only reach ·55 ton per square inch pressure, and the work done would be 5,833 foot-tons, which would fix the lower limit. It is certain that the gases, at the moment when the shot leaves the muzzle, have a much higher temperature than 960° absolute. The work done in the bore of the gun, we shall see presently, amounts to about 31,361 foot-tons, corresponding to 90,996 units of heat, which must disappear, as heat, from the powder gases; the fall of temperature, consequently, will be $t = \frac{90{,}996 \text{ lbs.}}{300 \text{ lbs.} \times \cdot 183} =$ 1,639°, which, deducted from the temperature 4,420° due to energy of chemical action in the combustion of the powder, leaves 2,781° absolute as a possible temperature at the moment of the shot leaving the gun, if no allowance be made for a farther fall caused by loss of heat expended in warming the gun and shot. This temperature is only 621° higher than that which has been assumed.

The usual method adopted in artillery text-books of estimating the energy expended in expelling the powder-gases, when it is not overlooked altogether, is to consider that from one-half to the whole weight of powder is expelled at the same velocity as the shot. But this is mere assumption, without any rational foundation, and takes no account, either of the proportions of the gun or the pressure in the bore, the latter being a function of the nature of the powder and mode of ignition. Upon the whole it seems tolerably correct to assume that the energy expended

in the expulsion of the powder-gases should be taken on the supposition that they are blown out of the gun at the velocity corresponding to their ascertained pressure, at the moment when the shot leaves the muzzle. The formula based on this view is

$$\text{Velocity of gases} = 4{,}544\sqrt{\frac{\left(\begin{array}{c}\text{Pressure in tons}\\ \text{per square inch}\end{array}\right)\times\left(\begin{array}{c}\text{Volume of bore}\\ \text{in cub. feet.}\end{array}\right)}{\text{Weight of powder in pounds.}}}$$

When the weight and velocity are known, the energy is, of course, easily calculated. The terminal pressure is difficult to arrive at. No gauges yet invented give trustworthy results, because the time during which the record has to be taken is so short. The estimates which can be formed, however, will be considered presently. It may seem strange that the pressure curve in the bore of a gun cannot be determined by direct calculation, but the reason is, that the powder continues to burn and evolve gas during the greater part of the time that the shot is travelling along the chase, and, as the rate of evolution is unknown, of course no formula can be constructed on purely theoretical considerations.

3. The displacement of the atmosphere. Allusion will be made later on to the rapidity with which the gases are expelled from the gun. It will suffice for the present to state, that the action is extremely rapid, and that the reaction to the effort of parting the air must be a pressure on the base of the bore.

We have assumed a temperature of 2,160° for the gases at the moment of the shot leaving the muzzle. The pressure due to gases at 50°, suddenly compressed into the gun, we found to be 1·03 tons per square inch, and the temperature 960·1°. The pressure corresponding to 2,160° would be equal to

$$\frac{1\cdot03 \text{ tons} \times 2{,}160°}{960\cdot1°} = 2\cdot32 \text{ tons}$$

per square inch, or 5,149 lbs. In expanding suddenly, the temperature would fall to

$$t = 2{,}160^\circ \left(\frac{1 \cdot 7 \text{ lbs.}}{5{,}194 \text{ lbs.}} \right)^{\cdot 125} = 1{,}037^\circ$$

and the volume would become

$$\frac{1{,}395 \text{ c. ft.} \times 1{,}037^\circ}{510^\circ} = 2{,}837 \cdot 4 \text{ c. ft.}$$

Deducting 5 cubic feet for the volume of the solid powder, we have 2,832·4 cubic feet of air displaced. The work of doing this will be—

$$W = \frac{2{,}832 \cdot 4 \text{ c. ft.} \times 2{,}117 \text{ lbs.}}{2{,}240 \text{ lbs.}} = 2{,}677 \text{ foot-tons.}$$

4. The rifling of the gun causes the shot to spin on its longitudinal axis as it traverses the bore. The angle of the rifling at the muzzle is such that the shot makes one revolution in thirty calibres, that is, in 300 inches, or 25 feet; hence, dividing the muzzle velocity by 25, we get the revolution per second to be 84. Now the diameter of the circle of gyration of a cylinder 10 inches in diameter is 7·072 inches, and its circumference 1·851 feet; therefore, at 84 revolutions per second, the velocity at the circle of gyration will be 1·851 feet × 84 = 155·52 feet per second, and the energy

$$\frac{500 \text{ lbs.} \times 155 \cdot 52^2}{2{,}240 \text{ lbs.} \times 64 \cdot 4} = 83 \cdot 82 \text{ foot-tons.}$$

The reaction to this motion is twofold. Firstly, the resistance of friction of the rifling balanced by the pressure of the gases, and therefore a self-contained strain; and secondly, a tangential pressure, tending to rotate the

shot, balanced by an effort to turn the gun in the opposite direction. Neither of these motions has any effect on the recoil.

5. The friction of the gas check is a matter of pure estimate, especially with the ring checks now in use. Assuming a mean pressure of powder gases of 12 tons per square inch, and supposing a copper band of $\frac{1}{2}$ inch effective depth pressed against the surface of the bore with that pressure, then taking the coefficient of friction at ·14 we have a surface of 15·7 square inches in contact under a pressure of 12 tons, and a space passed over of 22·5 feet, the work done will therefore be—

$$15 \cdot 7 \text{ sq. in.} \times 12 \text{ t.} \times \cdot 14 \times 22 \cdot 5' = 593 \cdot 5 \text{ foot-tons.}$$

The force assumed is equivalent to a pressure of ·35 ton per square inch on the base of the shot, or ·87 ton per lineal inch of circumference. Actual experiment has shown that to force a shot slowly through the bore requires a pressure of half a ton per square inch in the smaller guns, but necessarily this is a very variable and uncertain quantity.

6. The energy expended in stretching the gun and compressing the shot and breech block is very difficult to estimate. The 10-inch gun is supposed to have a factor of safety of about four, so we may assume that the metal is impressed with a strain of six tons per square inch. The mean volume of the gun, that is the volume to the centre of the metal, is about 49·45 cubic feet, and this will probably stretch to 49·696 cubic feet, absorbing ·246 c. ft. × ·144 sq. in. × 6ft. = 212·5 foot-tons. The strain, however, does not come on uniformly, but follows the shot along the bore, giving rise to a wave-like motion which must produce cross strains difficult to estimate, but

very serious, especially where guns are built of rings suddenly changing very much in diameter. There are, besides, other sources of vibration. The powder burns unequally, and most probably the gases evolved are traversed by pulses which must be communicated to the metal which confines them. In the modern long light guns, the weight of the shot, as it travels along the bore, sensibly depresses the muzzle, and this movement is aggravated by the powder heating the upper half of the gun more quickly, and to a greater extent, than the lower. The moment the shot leaves the muzzle, the barrel springs upwards, and vibration, which is said to be actually visible to the eye, is set up. Again, the powder gases, as they rush out, rub so hard against the sides of the bore that they actually, in places, erode the metal, and must produce longitudinal pulses similar to those which we have seen induced by friction in the brass and glass tubes of the apparatus for demonstrating the existence of molecular motion producing sound.

The simultaneous occurrence of vibrations of different wave length and intensity in a gun, implies that there will be interference, that is to say, as in the case of waves of sound or undulations in water, waves may coincide and produce a more intense effect, or, on the other hand, they may neutralise each other wholly or in part. It is well known that guns of different calibre and different metal have each their peculiar ring, which is audible through the main sound of the discharge, like overtones on a fundamental note in music.

Messrs. Chernoff and Beck-Gerhard, of St. Petersburgh, have noticed and described the manner in which sudden strains, such as those caused by punching, shearing, or hammering, are propagated through steel plates. By

operating on polished plates, Fig. 36, they have been able to render the waves of strain not only visible to the eye, but sensible to the touch, because the metal is strained beyond its elastic limit both in tension and compression, and consequently remains impressed with wave-like hollows and ridges. Mr. Chernoff suggests that similar abnormal lines of strain may arise in the metal of guns, and lead to the otherwise unaccountable failures, especially of inner tubes, which so often take place.

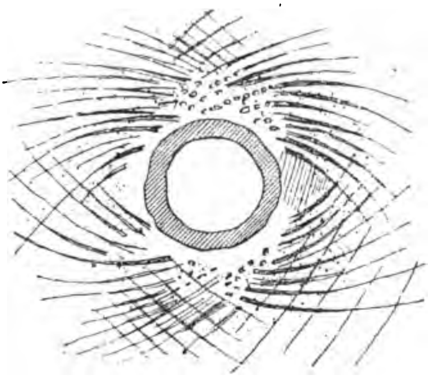


Fig. 36.

7. The friction of the powder-gases against the sides of the bore it is impossible to calculate with even an approach to accuracy, because we cannot tell whether the laws and coefficients applicable to ordinary temperatures and pressures will apply under the circumstances. Yet supposing that they do, and that the hot powder-gases behave like air, we may take the ordinary formula based upon the law which declares that the friction of air in pipes, when measured by the height of a homogeneous column of the same density, h, varies directly as the length of the pipe, l,

as the square of the velocity v, and inversely as the diameter of the pipe; and adopting the coefficient given by Weisbach—namely, $\frac{\cdot 217}{\sqrt{v}}$, we have, assuming the mean velocity to be 1000 feet per second,

$$h = \frac{\cdot 217 \times l \times v^2}{\sqrt{v} \times d \times 2g} = \frac{\cdot 217 \times 26 \text{ feet} \times 1000^2 \text{ ft.}}{\sqrt{1000} \text{ ft.} \times \cdot 833 \text{ ft.} \times 64 \cdot 4} = 3{,}326 \text{ feet.}$$

We have assumed a mean pressure in the bore of 12 tons per square inch, or 1,829 atmospheres; consequently the weight of a column 3,326 feet high and 10 inches diameter will be—

$$= \frac{3326 \text{ feet} \times \cdot 081 \text{ lb.} \times 1829 \text{ atmos.} \times 78 \cdot 5 \text{ sq. in.}}{2240 \text{ lbs.} \times 144 \text{ sq. in.}} = 120$$

tons—that is to say, it will require a push of 120 tons to overcome the friction of the gases against the bore at the enormous rate and pressure at which they travel. The work done will be 120 tons × 26 feet = 3,120 foot-tons. This may seem an altogether exaggerated estimate, but it must be remembered that the friction of gases increases as their pressure and as the square of their velocity, and that we are dealing with very high figures in both respects. It is also well to note that the friction of the gases close to the powder chamber (Fig. 35), where the temperature and pressure are greatest, and where they expand after the temporary contraction caused by passing the shoulder of the chamber, and therefore strike with increased energy against the bore, is sufficient to score and rasp away the metal, and become, by that means, the chief agent in the deterioration of guns.

A striking evidence of the force required to expel

powder-gases, and overcome their friction, is afforded in the difference of pressure recorded by crusher gauges when placed in the base of the bore, and in the base of the shot. In the experiments made to ascertain the cause of the bursting of the *Thunderer's* gun, this difference of pressure was as much as 5 tons per square inch out of 15·2 tons, or 33 per cent. of the pressure necessary to expel the shot, though the weight of powder was only 85 lbs. for a projectile weighing 590 lbs., or $14\frac{1}{2}$ per cent.

Collecting all the items we have been discussing into the form of a balance-sheet, we find that the discharge of the 10-inch gun performs 27,350 foot-tons of external work, and 4,011 foot-tons of internal work. The available energy of the powder is 73,658 foot-tons; hence there remains a balance unaccounted for on the credit side of 42,297 foot-tons, which must have been chiefly expended in communicating to the metal of the gun the molecular motion which becomes apparent in the form of heat. This energy represents

$$\frac{42{,}297 \text{ foot-tons} \times 2{,}440 \text{ lbs.}}{772'} = 122{,}730 \text{ units.}$$

The gun and shot weigh 60,880 lbs., and being of steel, have a specific heat of ·119, therefore the rise of temperature of the gun from each discharge may be expected not to exceed

$$\frac{122{,}730\ u}{60{,}980 \text{ lbs.} \times \cdot 119} = 16 \cdot 9^\circ.$$

This temperature will be very unequally distributed, and very quickly dissipated by radiation and conduction from the large surface of the gun.

Dr. **Balance-sheet of 10-inch Gun.** *Cr.*

	Foot-tons.			Foot-tons.	Foot-tons.	Per cent.	Per cent.
			I.—External Work.				
		1	Energy of shot . . .	15,285			
		2	" of expelled gases	9,388			
		3	" in displacing air.	2,677	27,350	37	87
			II.—Internal Work.				
Available energy of 300 lbs. of powder working between 4,420° and 2,160° absolute. .	73,658	4	Energy of rotation . .	84			
		5	" in friction of gas checks.	594			
		6	Energy in stretching gun	213			
		7	" in friction of gases	3120	4,011	5	13
		8	" in heat imparted to gun and shot = 16·9°.	44,297	42,297	58	
	73,658				73,658	100	100

Referring again to the balance-sheet, we have estimated that the external work done in the discharge amounts of 27,350 foot-tons, composed of three items, one of which, the energy necessary to expel the powder-gases, is uncertain. The work being external, there must be the same amount of work in the recoil, because, according to the third law of motion, to every action there must be an equal and opposite reaction, and, therefore, the quantity of motion must be the same. The pressure producing recoil lasts only so long as the shot and powder-gases are being expelled from the gun, and consequently the time during which the maximum velocity of recoil is reached must be the same as the time consumed in the discharge, for acceleration ceases the moment the accelerating force ceases to act. Recoil, however, does not become visible simultaneously with the discharge, because a certain interval of time is necessary to transmit the pressure against the base of the bore of the gun to its carriage, so as to cause the latter to move. The gun stretches longitudinally, the

trunnions compress the metal of their bearings, the material of the carriage stretches, and hence an appreciable delay occurs before visible motion begins, but the delay is made up for by the persistence of the motion for some time after the discharge, because the reaction to the stretching of the system keeps up the acceleration. An interesting illustration of this fact was afforded in the case of the short 6·6-inch muzzle-loading gun, mounted on a Moncrieff hydropneumatic carriage. The muzzle of the gun, when in the firing position, happening to be close to the concrete parapet, the powder-gases, the instant the shot left the muzzle, flashed out as a disc of fire, and marked the parapet as sharply as if it had been done with black paint, and the margin of the discoloration next the gun was exactly in line with the muzzle when in firing position, proving thereby that no sensible motion of the whole gun had commenced till after the shot had left the bore. In addition, although the gun recoiled instantly below the parapet, starting into motion at the rate of 22 feet per second, so that the muzzle of the gun must have been below the parapet in about $\frac{1}{20}$ of a second, yet not the slightest discoloration of the concrete was observable on the inside of the parapet even after many rounds. This is the evidence which has been alluded to in support of the statement that the gases are wholly expelled from the bore in a very short space of time, and must exert a correspondingly serious effect on the recoil of the gun.

But not only must the accelerated motion of recoil take place in the same time as that occupied by the discharge, but because, according to Newton, velocity is proportional to the impressed force, the rate of acceleration of the shot and gases as they move along the bore at each instant, must have its counterpart in the motion of recoil; hence

the curve of velocities of recoil, could we construct one, would correspond to that for the velocities in the bore, but on a reduced scale. Because of the quantity of motion in the discharge and recoil being equal, and of the weight of the gun and its carriage being much greater than that of the shot and gases, the motion of the former will be so much slower than that of the latter, and therefore more easily registered. But how are we to obtain a faithful picture of the motion of recoil? The answer is, by means of a beautiful instrument invented by Colonel Sebert, of the French marine artillery.

This apparatus consists of a solid pedestal secured to the ground beside the gun-carriage. A tuning fork is fixed to the pedestal, and kept in vibration by means of a galvanic current. To one prong of the fork is attached a stile or tracer, so arranged that it will scratch a wavy line upon a strip of blackened metal, one end of which is attached to the carriage, which, in recoiling, draws the strip along under the tracer. The tuning fork is adjusted to make 500 complete vibrations per second: this corresponds very nearly to the middle C of the musical scale. If a centre line be drawn through the undulations, each complete beat will cut the line twice, so that each intersection will measure the $\frac{1}{1000}$ part of a second, and the pitch of each half wave will be the distance passed through in that minute fraction of time. The diagram traced will therefore give all the information which we require, namely the total time of the accelerated motion of recoil, which will be up to the point where the waves attain their maximum pitch, the maximum velocity of recoil, and the rate at which the recoil is accelerated throughout, so that, knowing the weight of the gun and its carriage, we can determine the energy at any point, and, as has been already stated, this

must be the counterpart of what takes place in the bore. A special instrument, provided with micrometers and a magnifying glass, is used for measuring the pitch, the amplitude of the vibrations, and the angles at which the wave line cuts the centre line.

A simple apparatus, Fig. 37, will illustrate Sebert's instrument. Over a pulley secured to the top of a tall stand is passed a cord, to one end of which is attached a lath covered with a strip of paper, and to the other end is hung a weight, so adjusted as to give a moderate speed to the lath. As we saw in the first chapter, the lath will move with uniformly accelerated velocity. In front of the lath hangs a pendulum, which makes a double swing in one second. Attached to its rod, near the point of suspension, is a pencil, which presses on the paper. The lath is first allowed to rise, while the pendulum is stationary; the pencil traces a straight centre line. It is then drawn down, and the pendulum is set swinging; the pencil traces a short arc. If the lath be now released, it will move upward, and the pencil will trace a wavy line, which intersects the centre line previously traced. Each intersection defines the space passed through in half a second, and when we measure the total lengths cut off in 1, 2, 3, 4 half-seconds, we find them to increase in the ratio of 1, 4, 9, and 16, which we know to be the rate of increment proper to a continuously acting force, such as gravity. On the diagram, Fig. 38, this wave-line has been drawn. Hence, suppose the

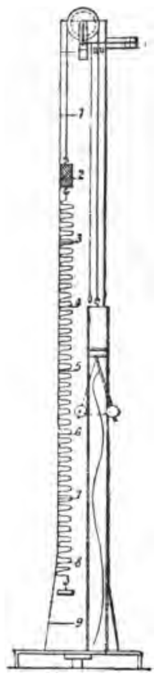


FIG. 37.

Sebert machine were to trace one like it, we should know at once that the pressure of gases in the bore of the gun must also have been uniform throughout the discharge.

We now balance the weight of the lath exactly, and attach a spiral spring, which forms part of the balance weight, to the cord by which the lath was raised. In pulling down the lath the spring is brought into tension. The pendulum is started and the lath let go; a curve is traced which represents velocities produced by a uniformly decreasing accelerating force, such as a spring. This curve also is represented on the diagram, Fig. 38, and were the Sebert apparatus to trace such a curve, we should know that the pressure in the bore was uniformly decreasing.

In all cases, supposing the carriage to recoil down an incline which would exactly compensate for friction, the curve, whatever its nature might have been during acceleration, would terminate in waves of equal pitch, corresponding to the maximum velocity attained, because, according to the first law of motion, the carriage would continue to move at a uniform velocity so soon as the impelling force ceased to act. The proper way, therefore, to measure the recoil, is to mount the gun on a well-made carriage, placed on an evenly laid line, which would, for the first two or three feet, fall in the direction of recoil at an incline corresponding to the friction of the carriage, and, after that, rise at any convenient rate sufficient to take up the energy imparted. It is hardly necessary to add that the work done in arresting the recoil will be equal to the work done in obtaining its maximum velocity, and also to the external work of the discharge, so that the determination of the second portion of the recoil will serve to check the first. Up to the present, these two distinct parts of

recoil appear to have been mixed up together, and no deductions as to the rate of work in the bore have been made from either of them. When the wave line has been obtained, it is easy to calculate the velocity at each intersection with the centre line. The motion there is compounded of the maximum velocity of the tuning fork and the velocity of recoil. If a tangent be drawn to the wave line at the intersection with the centre line, Fig. 38, then the tangent of the angle a made with the centre line will be represented by the velocity of the fork divided by the velocity of recoil.

The amplitude of the fork's vibrations is constant throughout, and may be measured on the diagram. The maximum velocity, which occurs when the stile crosses the centre line, is

$$v = \frac{\pi \times \text{amplitude of vibration}}{\text{time of a complete vibration}}, \text{ and the}$$

$$\text{velocity of recoil} = \frac{v}{\tan.\ a.}$$

Suppose the amplitude to be $\frac{1}{100}$ of a foot and the number of vibrations 500 per second, then the maximum velocity $= \dfrac{3 \cdot 1416 \times \cdot 01 \times 500}{1} = 15 \cdot 7'$.

Suppose the curve crosses the centre line at an angle of $31\frac{1}{2}°$, then the speed of recoil will be $= \dfrac{15 \cdot 7'}{\tan.\ 31\frac{1}{2}} = 25 \cdot 62$ feet per second. The numerator will be a constant for each instrument.

The investigations which we have gone into are intended to lead up to the determination of the pressure of the powder gases in the bore of a gun. These pressures are, up to the present, unknown, except so far as they have

been determined by the unsatisfactory agency of crusher gauges.

Referring to the balance-sheet, it will be observed that

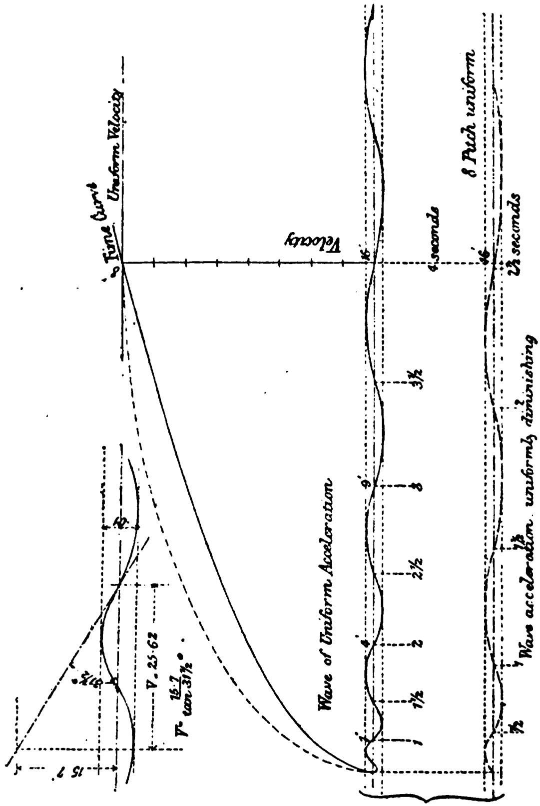


FIG. 38.

the external work of the discharge forms nearly 37 per cent. of the whole work of the powder, and the internal work only 5 per cent., or, of the total mechanical work, the external is 87 per cent., while the internal is only 13

per cent., so that any error in estimating the several items of the latter will not sensibly affect the inferences to be drawn from the observations on the first portion of recoil. In the external work, also, the only uncertain item is the energy absorbed in the expulsion of the powder-gases; hence, if, by means of the Sebert apparatus, we can determine the total external work, we can also determine exactly the uncertain item in our balance-sheet.

The total mechanical work is equal to 31,361 foot-tons, and suppose that this were performed at a uniform rate throughout the stroke of 22 feet, we should have an average push of $\frac{31{,}361 \text{ foot-tons}}{22 \text{ ft.}} = 1{,}425 \cdot 5$ tons; dividing this by the area of the base of the shot, 78·54 sq. in. gives an average pressure to the powder-gases of 18·15 tons per square inch. The maximum pressure attained by the gases at the commencement of the discharge is believed to be about 22 tons per square inch, but it is probably considerably higher; and the lowest pressure, namely, that at the muzzle—calculating on the assumption that the temperature is 1,700°—about 2·32 tons: so that an empirical curve may be traced, which, between those limits, would include an area equal to the work done. If, however, the first part of recoil can be pictured by means of the Sebert velocimeter, and a curve of velocities obtained, it does not matter how irregular the curve may be, the pressures in the gun can be calculated in the following manner. The fact that the velocity of recoil is increasing implies that an impressed force is acting: hence, selecting two points in the recoil at a short measured distance from each other, ascertain, by measuring the curve, the velocities at the two points. Let them be V_1 and V, Fig. 39. The energy latent in the higher

velocity will be $\frac{W}{2g} V_1^2$; and the lower $\frac{W}{2g} V^2$, the difference $\frac{W}{2g} (V^2_1 - V^2)$ must have been due to a pressure acting through the space S between the points $= P\ S$, hence the mean pressure—$P = \frac{W}{2gS} (V_1^2 - V^2)$. As we know all the terms on the right side of this equation, the pressure P on the carriage will be known, and that will also be the pressure on the base of the bore at the corresponding period of discharge. If we divide this by the area of the bore, the pressure per square inch follows at once. In this way a curve of pressures in the bore may be accurately arrived at.

In addition to the tuning fork, the Sebert machine has stiles fixed to the armatures of electro-magnets, the attractions of which, so long as the current is passing, keep the stiles immovable; consequently, when the gun recoils, the stiles trace a straight line close beside the wavy line of the tuning fork. The wires from the electro-magnets are, however, carried across the line of fire, one just in front of the muzzle, a shot length off, and a pair through the ordinary velocity screens. As soon as the shot breaks the wires, the armatures leave their magnets, and their stiles make a kink in the line they trace. The relative positions of these kinks, as to time and space, are defined by the undulations of the line traced beside them by the tuning fork. In this way the exact moment when the shot leaves the gun is ascertained. If the wave line has reached its maximum pitch before the shot leaves, then the gun is too long; if, on the other hand, acceleration of motion is still going on, then the gun is too short to absorb all the energy of the powder.

We can make an approximation to the recoil on the

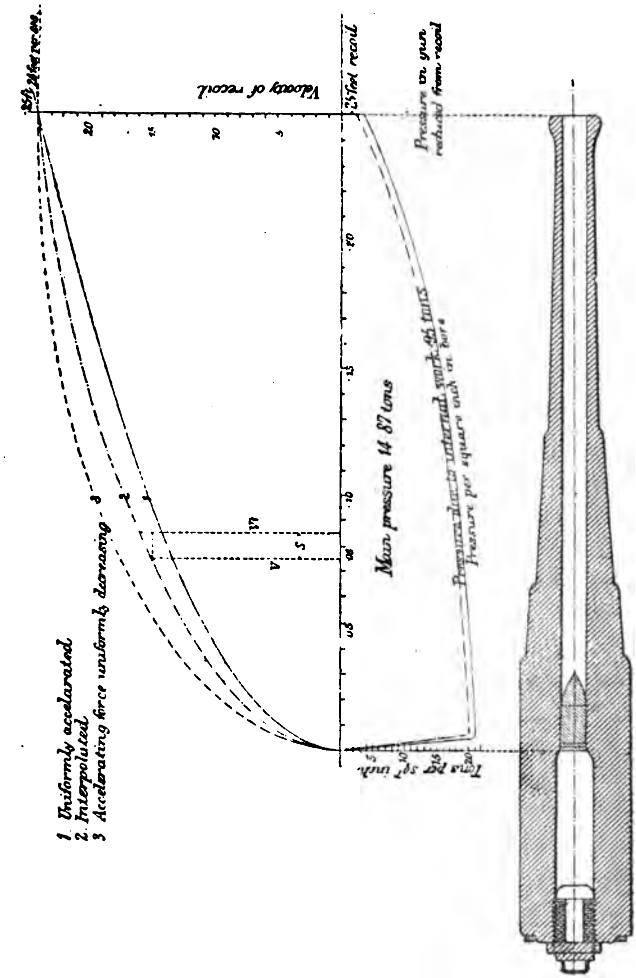


FIG. 89.

assumption that the pressure in the bore throughout the discharge is constant, that the powder-gases and shot are expelled at the same velocity, that the space passed

through in the bore is 22 feet, and that the gun carriage weighs five tons, so that gun and carriage together weigh 32 tons. The powder and shot together weigh 800 lbs., or ·357 ton; we assume that they are expelled at a speed of 2,100 feet per second. Then, because of the equality of the quantity of motion, the maximum velocity of recoil will be

$$= \frac{2{,}100 \text{ ft.} \times \cdot 357 \text{ ton}}{32 \text{ tons}} = 23 \cdot 42 \text{ feet per second.}$$

The time of discharge, which will also be the time of the acceleration of recoil, $= \frac{2S}{v} = \frac{44'}{2100'}, = \cdot 02095$ second.

The space passed through during the accelerated motion of recoil will be

$$= \tfrac{1}{2}\, t\, v = \frac{0 \cdot 02095 \text{ sec.} \times 23 \cdot 42 \text{ feet}}{2} = \cdot 245 \text{ foot, or nearly}$$

3 inches.

The rate of acceleration during recoil $= \frac{v^2}{2S} = \frac{23 \cdot 42^2}{2 \times \cdot 245'} = 1{,}118$ feet per second, corresponding to the value of g in gravity; hence the accelerating force will be $\frac{32 \text{ tons} \times 1{,}118 \text{ feet}}{32 \cdot 2 \text{ feet.}} = 1{,}111$ tons.

The rate of acceleration in the bore of the gun $= \frac{2{,}100^2}{2 \times 22} = 100{,}230$ feet per second, and the accelerating force, $= \frac{\cdot 357 \text{ ton} \times 100{,}230 \text{ feet}}{32 \cdot 2} = 1{,}111$ tons; that is to say, the pressure on the breech, block, and against the carriage is the same, and equal to 1,111 tons, which, divided by 78·54 square inches, the area of the bore, gives

14·14 tons per square inch as the average pressure of the powder gases.

The energy of recoil

$$= \frac{32 \text{ tons} \times 23 \cdot 42^2 \text{ feet}}{64 \cdot 4} = 272 \cdot 7 \text{ foot-tons},$$

which figure is also arrived at by multiplying the accelerating force of 1,111 tons by the space it works over = ·245 foot.

Suppose the carriage, as soon as the maximum speed of recoil has been attained, is made to run up an incline of 1 in 10, it would rise $\frac{1}{10}$ of a foot for every foot of recoil, and would do 3·2 foot-tons of work. The resistance of friction would be about 8 lbs. to the ton weight of gun and carriage

$$= \frac{32 \text{ tons} \times 8 \text{ lbs.}}{2{,}240} = \cdot 144 \text{ ton per foot.}$$

so that the total resistance would be 3·304 foot-tons per foot of recoil, and, therefore, the gun will come to rest in

$$\frac{272 \cdot 7 \text{ foot-tons}}{3 \cdot 344 \text{ foot-tons}} = 81 \cdot 56 \text{ feet.}$$

It is very improbable, however, that the pressure in the bore can ever be uniform. Such an assumption is an extreme one, but we may take another extreme view, and suppose that the powder-gases act like a spiral spring, the tension of which varies as the distance through which it is compressed. Under such circumstances, the velocity of recoil will vary as the square root of the difference between the square of the full compression of the spring, and the square of the compression up to the point where the velocity is to be determined.

If P = pressure required to compress a spring one

M 2

foot, S = full range of compression, S_1 range of compression at any other point, W weight moved, and V the desired velocity, the tension of the spring compressed to a distance $S = P\,S$, and its potential energy will be $= P\,S \times \frac{S}{2} = \frac{P\,S^2}{2}$. The kinetic energy would be $\frac{W\,V^2}{2\,g}$ and that must be equal to the potential $\because \frac{P\,S^2}{2} = \frac{W\,V^2}{2\,g} \therefore P = \frac{W\,V^2}{g\,S^2}$. At any other point, S_1 feet compression, the energy is the total energy due to the compression S less that due to S_1

$$= \frac{P\,S^2}{2} - \frac{P\,S_1^2}{2} = \frac{P}{2}(S^2 - S_1^2) = \frac{W\,V^2}{2\,g} \quad V^2 = \frac{P\,g\,(S^2 - S_1^2)}{W}$$

$$\text{and } V = \sqrt{\frac{P \times g}{W}} \times \sqrt{S^2 - S_1^2} = a\sqrt{S^2 - S_1^2}$$

The curves of velocities which will produce a speed of recoil of 24 feet per second, in one quarter of a foot have been calculated and plotted on the diagram (Fig. 39). The ordinates in curve No. 1 give the velocities due to a uniform pressure; the curve cuts the line of uniform velocity of 24 feet per second at an angle which indicates that the pressure must cease suddenly when the desired velocity is attained. Curve No. 3 gives the velocities, supposing the force to be of the nature of a spring, consequently the line of uniform velocity is a tangent to it, which indicates that the accelerating force ceases to act gradually, and, when the full velocity is attained, acts no longer.

The true velocities lie between these two, along the interpolated curve No. 2, which will probably not be far from the mark. This curve has no known equation, but the accelerating force has been ascertained in six places by the method already described, and by that means has been

obtained a curve of pressure acting against the carriage—that is, against the bottom of the bore of the gun. Dividing this by the area of the bore, the pressure per square inch is obtained, and by changing the scale of the diagram, so as to make the base line represent the length of the chase, we get a curve of the powder pressure along the whole bore. The maximum pressure comes out about 20½ tons per inch, the minimum 2½ tons, and the mean pressure 14·87. The area of the figure bounded by the curve of pressures will give the external work done; the figure is, in fact, an indicator diagram of the gun, but is still incomplete, for we must add 13 per cent. to the pressures, amounting to nearly two tons per square inch, to represent the internal work, which does not affect the recoil. This has been added as a constant pressure throughout, though it may not be so, but, as may be seen from the diagram, the amount is small, and will not much affect the accuracy of the result, in what manner soever the pressure may really vary.

It has been said that the indications of the crusher gauges, upon which so much reliance is placed, are untrustworthy. The reason for thinking so is because time is an element in the complete action of a shortening or extending movement in a metal cylinder; hence, in order that the indications given by compression may be comparable, the time during which the forces act must be either long enough to allow the whole effect to take place, or, at any rate, the same in all the experiments. Now the compression of the little copper cylinders of the crusher gauges take place in very short and very unequal times. The gauge in the breech is much longer exposed to the action of pressure than in the muzzle, yet the change of length is compared uniformly with pressure slowly applied,

and therefore the indications of the gauges are sure to be too low. This view is confirmed by the extraordinary coincidence between the pressures indicated by crusher gauges and those derived by calculation from increments in the velocity of shot as it traverses the bore. This velocity has been ascertained by Captain Noble by means of a chronograph, which registered the time of the shot passing certain points in the chase. We have already seen how, from a curve of velocities, the pressure can be calculated; it is found that the crusher gauges indicate the pressures due to the accelerated motion of the shot only; hence, either their indications are erroneous, or else we must conclude that the powder-gases have no weight, that there is no atmosphere to displace, no friction of gas check or gases, and no work in producing rotation. This error is by no means a trifling one, for the balance-sheet indicates that the items just mentioned form over 50 per cent. of the whole mechanical work done.

The pressure curves we have obtained are certainly very different from those generally received, which are convex to the gun and not concave, showing a much more rapid fall of pressure along the chase than we have arrived at. Experience has shown, however, that our guns were weak in front of the trunnions, and they have been greatly strengthened; the 10-inch gun, for example, now weighs 32 tons instead of 27 tons, the additional 5 tons being placed nearly all in front of the trunnions.

In some recent trials at Shoeburyness with a 6·6-inch muzzle-loading gun, mounted on a Moncrieff carriage, the pressures were taken by means of crusher gauges, both in the base of the bore and close to the muzzle. Ten rounds were fired with precisely the same charges, the crusher gauges in the powder chamber registered pressures varying

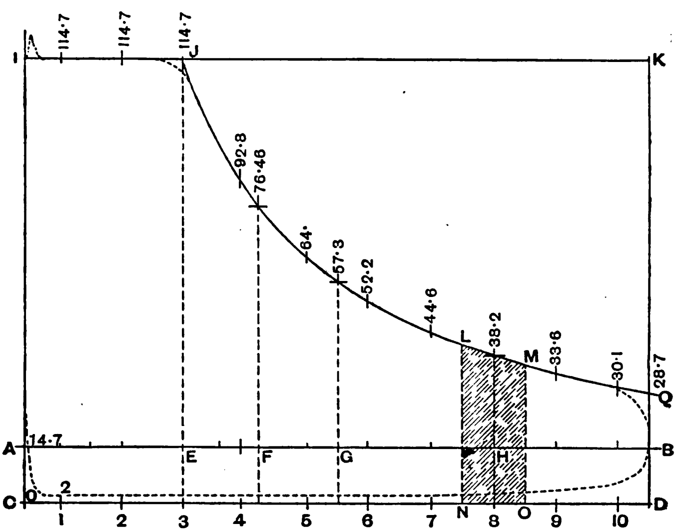
from 12·4 tons to the square inch to 13·7 tons, while the gauges near the muzzle were very wild in their indications, the pressures varying from one ton per square inch to five tons. The indications in the chamber were fairly consistent with each other, because the time during which the gauges were exposed to pressure was very much greater than at the muzzle, so that when the time of exposure is very short, crusher gauges cannot be trusted to give even good comparative results.

Hydro-pneumatic carriages for disappearing guns furnish a very good means of measuring the intensity of recoil, because it is taken up chiefly by the compression of air. In the carriage for the 6·6-inch gun already alluded to, the calculations for the necessary air pressures were made upon the principles here laid down; the result of the trials at Shoeburyness indicated that the calculated recoil was realised within two or three per cent., demonstrating that the estimates of the force of recoil are not very far from the truth.

CHAPTER VI.

We are now prepared to consider heat-engines proper, that is to say, mechanical contrivances more or less complicated, whereby the heat imparted to the agent is converted into work; but a preliminary step must be a short description of the indicator, an instrument which is used for the purpose of depicting automatically the changes of volume and pressure which take place in the agent when a heat-engine is working. Nearly all heat-engines are actuated by heated expansive gases pressing upon pistons working in closed cylinders or spheres, and the amount of work which is performed is proportional to the volumes described by the pistons, multiplied by the mean pressure exerted against them. The indicator is merely a small working cylinder which can be placed in communication with that of the engine. The cylinder has usually an area of half a square inch, and is fitted with a piston, to the rod of which is attached a pencil, arranged so as to trace a line on a paper-covered roll which is made to rotate with a reciprocating motion at a speed proportional throughout to that of the piston of the engine. The indicator piston is held down by a spring the elasticity of which is accurately known. When there is no communication between the two cylinders, and while the paper-roll is turning backwards and forwards isochronously with the piston of the engine, if the pencil be applied, a straight line will be

traced; this line will represent the atmospheric pressure, or one atmosphere. As soon as the connecting cock between the cylinders is opened, the indicator piston, with its rod and pencil, commences at once to follow the movements of the larger piston, the range of motion depending on the pressure inside the large cylinder, the indicator spring yielding till its elasticity is balanced by the pressure of the agent. The pencil, if now applied to the paper, will trace a closed curve which represents, in the direction of the atmospheric line, the distance passed over by



the main piston, and, in the ordinates at right angles to the line, the pressures above or below the atmosphere. The area of the figure represents the work done, if the length of it along the atmospheric line be considered to represent the volume of the cylinder.

Figure 40 is an indicator diagram such as is obtained from a single cylinder condensing steam engine.

The paper, which was secured round the roll, when the figure was traced, is here laid out flat. A B is the atmospheric line, and the ordinates above and below it denote pressures, while its length between the perpendiculars I C and K D represents either the stroke of the piston, or the volume it sweeps through, which is directly proportional to the stroke. C D represents absolute vacuum, which may be taken at 14·7 lbs. per square inch, or 30 inches of mercury below the atmosphere (760 mm. is the metric standard equal to a pressure of 1·033 Kilogramme on the square centimetre).

If steam were carried on for the whole stroke and exhausted without resistance into a perfect vacuum, the pencil of the indicator would trace the rectangle I K C D.

If, however, as is usually the case, steam be shut off before the piston has completed its full stroke, then the imprisoned steam must expand and, supposing that it does so without change of temperature, which, as we shall see later on, is very nearly the case, the pressures will fall according to the ordinates of an isothermal curve. Supposing we have 100 lbs. per sq. inch pressure above the atmosphere, then $p=114\cdot7$ lbs. absolute, and if we cut off the steam at J, say one fourth of the stroke, we can easily calculate the expansion curve J Q according to Boyle's law—

$$p_1 = p\frac{v}{v_1}$$

where A E $=v$, and v_1 represents the successive volumes between A E and A B.

The indicator pencil will trace the figure I J O D C.

The work done in moving A to E will be $p\,v$, and in moving from E to B it will be $p\,v \log^e \frac{v_1}{v}$, the total work will therefore be $p\,v + p\,v \log^e \frac{v_1}{v}$ $W = p\,v\left(1 + \log^e \frac{v_1}{v}\right)$ and since v_1, multiplied by the mean pressure throughout the stroke will also be equal to the work, it follows that $\frac{W}{v_1}$ = mean pressure, therefore mean pressure

$$= \frac{p\,v}{v_1}\left(1 + \log^e \frac{v_1}{v}\right).$$

Since the stroke is directly proportional to the volume, $\frac{v}{v_1} = \frac{A\,E}{A\,B} = \frac{1}{R}$, or the rate of expansion, and therefore the mean pressure $= \frac{p}{R}(1 + \log^e\ R)$ which is the formula usually given in pocket books.

In practice, however, the expansion curve differs considerably from the isothermal. The corner J is rounded, owing to the steam being shut off gradually and not suddenly. At Q the curve begins to fall some time before the end of the stroke is reached, because the "lead" of the valve opens the way to the condenser before the piston has completed its travel. Again, a perfect vacuum is unattainable, besides which the pressure in the condenser is momentarily increased by the admission of each cylinder full of steam and only reaches its minimum when the stroke is nearly completed, so that the dotted line B O represents what is termed the "back pressure," the average value of which varies from 2 lbs. to 51 bs. per square inch. At the point O the exhaust valve closes, and the corner is rounded because the steam left in the cylinder clearances and ports is compressed, and, generally the valve has a "lead" which

lets in the steam before the end of the stroke. The corner I is either sharp, or marked by a sudden jump in the pressure extending above the maximum in the boiler, this is caused by the sudden compression of the steam admitted before the turn of the stroke.

In consequence of these and other irregularities it is impossible to ascertain the work done, as indicated by the diagram, by direct calculation from the observed pressures and rate of expansion, but since the area of the figure is clearly the base A B multiplied by the mean ordinate or mean pressure, it follows that the area of the figure is proportional to the power indicated, or work done on the piston. The area of the figure can be measured by a planimeter, or by an approximate measurement of this kind. Divide the stroke A B into 10 parts and let the points 1, 2, 3, &c., be the centres of each $\frac{1}{10}$th part, then proceed upon the assumption that the curve L M, forming the upper boundary of the figure L N O M, is a straight line, calculate the work done in moving from N to O as equal to the mean pressure represented by the length of the line 8 multiplied by the volume N O. Inasmuch as the length N O is the same throughout the stroke, it follows that the total area will be equal to the base A B multiplied by the mean length of the ten ordinates 1, 2, 3, &c. If carefully done the results are very accurate. For example in the figure I J Q D C the mean absolute pressure measured from the diagram proves to be 69·96 lbs. per square inch, and, calculated by the formula given above, it is

$$W = \frac{114 \cdot 7}{4} (1 + \log^e 4) = 69 \cdot 84 \text{ lbs.}$$

The work done by the "back pressure" must be deducted from the above calculation. This can be ascertained by

measuring the back pressure at each of the ten points, and multiplying the mean by the volume A B, or, as is commonly done, the lengths of the ordinates at the ten points are measured between the two curves which gives the mean effective pressure at once. Strictly speaking, the back pressure on the opposite side of the piston should be deducted from the total absolute work, because the pressure on *one* side is opposed by resistance of back pressure on the other.

The horse power, which is the rate of work per minute, is found by multiplying the work done per stroke by the number of strokes per minute and dividing by 33,000 foot-pounds.

The values p and v, when the results are brought out in foot-pounds are most conveniently taken in pounds per square foot and in cubic feet, but when, as is commonly the case, gaseous pressures are quoted in lbs. per square inch, p must be multiplied by 144 square inches.

The indicator is far from being a perfect instrument. The curve it traces is affected by the inertia of the moving parts, by the defective elasticity of the spring, by friction, by the weight of water condensed about its piston, by the time which the pressure takes to travel along the connecting pipes, and by the stretching of the string or wire which turns the paper roll. All these sources of error increase with the increase of speed; nevertheless, the indicator diagram represents, with tolerable exactness, the changes of volume and pressure which take place in the working substance throughout a complete cycle.

The Gas-engine. (Fig. 41.)

In the case of the explosion of gunpowder in firearms, the working of the machine is intermittent. In repeating

guns, indeed, an approach is made to continuous working,

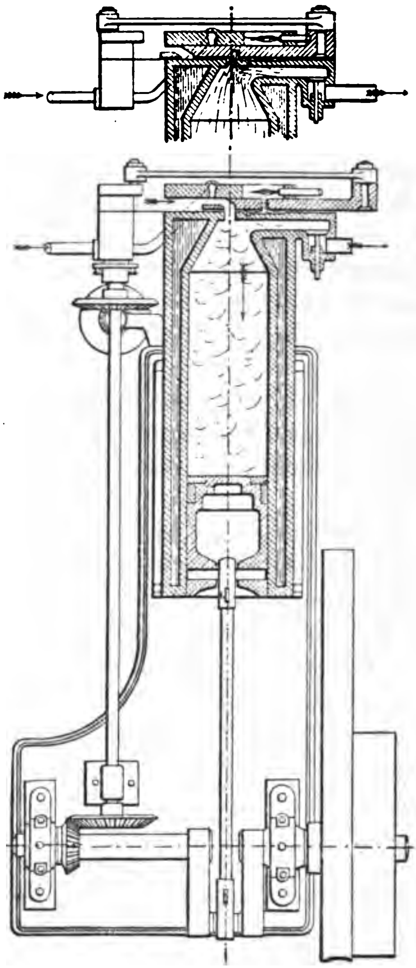


Fig. 41.

though, with the exception of the Maxim gun, not in an

automatic manner, but in gas-engines the force of explosion is made to imitate closely the action of a steam-engine.

The most successful of these motors is that known as the "Otto Silent Engine," we will, therefore, adopt it as a type of this class of apparatus designed for the conversion of heat into useful work. The engine consists of a cylinder fitted with a piston, which actuates a connecting rod, and by its agency a crank shaft, on which is keyed a fly-wheel, the whole arrangement resembling very much that of an ordinary horizontal steam engine.

The cylinder is longer than the stroke of the piston, so that at the rear end there is a space or chamber, having a volume of about 61 per cent. of the displacement of the piston. The other end of the cylinder is open to the atmosphere, and therefore the engine is single-acting—that is, the pressure of the working agent comes only on one side of the piston.

Not only is the engine single-acting, but the piston receives an impulse only once in every two revolutions of the fly-wheel, or once in four strokes. During the stroke in which the impulse is given—which lasts one-fourth of the complete cycle—the pressure accelerates the motion of the fly-wheel and other moving parts, and the energy so accumulated is given out during the remaining three-fourths of the cycle. The velocity of rotation necessarily varies in a proportional degree. For the purpose of keeping the cylinder cool, it is surrounded by a jacket, through which a stream of water continually circulates.

A complete cycle consists of the following operations:—

1. The piston makes a forward stroke, and draws in a supply of gas and air through a slide valve in the rear of the cylinder. At the end of the stroke, the slide valve closes the passages; and

2. The piston makes a return stroke, and compresses the air and gas into the chamber at the rear end of the piston.

3. The explosive mixture of gas, air, and the residue of the products of combustion of the previous stroke is ignited, very rapid combustion, rather than explosion, takes place, and is barely completed before the piston attains the end of its second forward stroke. The heated gases expand, giving out work, and accelerate the motion of the moving parts. When the end of the stroke is nearly reached, the exhaust valve is opened, and

4. The piston, in its second return stroke, partially drives out the products, and restores everything to the same condition as it was at the beginning of the cycle.

The principle of action will be best discussed in connection with an actual example, viz., that of a ten horse-engine experimented on by Messrs. Brooks and Steward, at the Stevens Institute of Technology in New York, in the year 1883.

This engine had a cylinder 8½ in. diameter by 14 in. stroke. We will select experiment No. 19, made when working full power. An indicator diagram (Fig. 42) was taken, and it sets forth all the changes which took place during one of the cycles. Let us consider the four strokes in detail.

1. The first outward stroke.—The indicator diagram shows that a vacuum, amounting to ·15 of an atmosphere, or 2·2 lbs. per square inch, was produced in drawing in the air and gas, the exact quantity of which, consumed during the 30 minutes run, was measured by accurate meters and found to be 3·76 lbs. of gas and 60·38 lbs. of air, being in the proportion of 1 : 16. The gas used was of inferior quality, and required only 12½ lbs. of air per

1 lb. of gas for perfect combustion, so that the quantity actually used was 28 per cent. in excess. With good gas, such as is generally supplied to London, it will be seen, from the table of "Properties of Fuels" (page 99), that 15·66 lbs. of air are required for a pound of gas.

2. In the return stroke, the air and gases were rapidly compressed into a little more than one-third of their volume. The engine made 160 revolutions per minute, so that the compression must have taken place in a little over one-fifth of a second, consequently we should have expected the pressure of the gases to rise nearly according to the ordinates of an adiabatic curve, such as has been

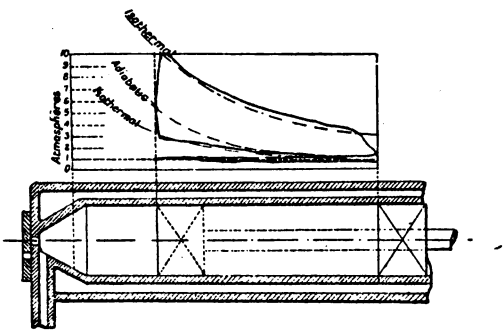


Fig. 42.

traced in dotted lines on the indicator diagram. The water-jacket, however, carried off the heat, due to the energy expended in compression, so fast, that the curve barely rose above the isothermal, which has also been indicated by a dotted line. The work, which was negative, that is, performed upon the agent, had been done at the expense of the energy latent in the fly-wheel, and had it been possible to prevent the escape of heat, no permanent loss would have been sustained, because the same amount

of work would have been given out on the return stroke; but, under the actual circumstances, energy, represented by the difference between the work done along the two curves, has been carried off by the water-jacket, and lost, so far as the engine is concerned.

3. At the turn of the stroke, the explosive mixture is fired by an ingenious arrangement in the slide valve, by means of which a pinch of gas—if the term may be used, is set alight by a jet constantly burning behind the valve, and carried, before combustion ceases, into the passage communicating with the cylinder through which the contents of the latter are ignited.

As will be seen by the vertical line on the left of the diagram, which represents the rise of pressure due to the explosion, the combustion is very rapid, and its intensity reaches a maximum before half an inch of the stroke is accomplished, or in about one-fiftieth part of a second, the pressure rising from three atmospheres absolute to ten, and then sinking as the volume of the gases increases. The fall of pressure ought to be according to the ordinates of an adiabatic curve; but in reality, as will be seen by the dotted line which has been introduced into the diagram, the curve rises a little even above an isothermal.

When within about 1½ inches of the end of the stroke, the exhaust valve begins to open; and, 4th, in the return stroke, the products of combustion are expelled at a temperature of 790°, or 1,250° absolute.

The gas used in this case, it has already been stated, was of poor quality. Mr. Deering has calculated its thermodynamic value, and he finds, supposing it to have been saturated with vapour of water, that the combustion of 1 lb. would yield 17,096 units of heat.

During the half-hour over which the observation ex-

tended, 3·764 lbs. of gas were used, the total weight of complete fuel and products was 84·711 lbs., and 20·568 lbs. of products of combustion at 1,250° absolute remained in the cylinder, consequently the mixture of gas, air, and products, taking due account of the variations of specific heat, must have had a mean temperature of 734° absolute. The indicator diagram shows that the temperature did not change sensibly during the compression of the mixture, hence the total heat of combination was $17{,}096^{u} + (734° \times \cdot 188) = 17{,}234^{u}$ per pound of gas, reckoning from absolute zero. The mean specific heat of the gases must here be taken as that due to constant volume, and proves on calculation to be ·188. The absolute temperature should rise to

$$\frac{3 \cdot 764 \text{ lbs.} \times 17{,}096^{u}}{84 \cdot 711 \text{ lbs.} \times \cdot 188} + 734° = 4{,}781°,$$

if chemical reaction were complete, but this temperature is higher than that at which dissociation takes place, so that it could not possibly be reached.

We can approximate to the true temperature, however, by calculating from the pressures which the indicator diagram declares. The temperature of the mixture of gases before explosion was 734° absolute, at 3 atmospheres pressure; this rose at once to 10 atmospheres, hence the temperature, allowing for the contraction of volume which takes place in the chemical reaction, and for the increase of volume due to the piston having moved forward half an inch, must have been $\dfrac{734° \times 10\, at \times 5 \cdot 82 v}{2 \cdot 964\, at \times 5 \cdot 32 v} = 2{,}712°$ absolute. This point is not capable of exact determination by calculation, because of the uncertainty as to the specific heats of substances at high temperatures. The true value must be somewhat higher than the figures arrived at, because the indicator, owing to its own friction and inertia,

is sure to register the pressures lower than they really are, especially when the action is so rapid, as it is in the case of gas-engines. It will probably be safe to assume that the maximum temperature attained was about 3,000° absolute. Under such circumstances, the duty to be expected, according to Carnot's doctrine, would be

$= \frac{3{,}000° - 1{,}250°}{3{,}000°} = \cdot 583$, and the total available power for which the engine might fairly be made debtor would be

$$\frac{3 \cdot 764 \text{ lbs.} \times 17{,}234'' \times 772' \times \cdot 583}{30' \times 33{,}000}$$
$$= 29 \cdot 49 \text{ horse-power.}$$

The circumstance that the expansion curve of the indicator diagram follows the isothermal, and not the adiabatic, and the lowness of the temperature when the maximum pressure is reached, show that combustion must continue for at least the whole stroke, and probably even some way along the return. It is only by such a supposition that the heat communicated to the working substance, as it expands, can be accounted for, because the metal of the cylinder, surrounded by its water-jacket, is much cooler than the gases, and, so far from heating, must tend to cool them. Again, working backward from the final temperature of 1,250°, the heat, at the moment of exhaust, should be about 1,800°, calculating from the pressures, whereas it is quite 1,000° higher, the excess being carried off during the return stroke by the water-jacket.

The engine must be credited with the following work:—

1. The indicated power ascertained by measuring the diagram, being the useful external work done = 8½ horse-power.

2. Heating up the 9·75 cubic feet of water which

passed through the jacket during the half-hour for which the experiment lasted to 43·38° Fahr., this represents—

$$\frac{9 \cdot 75 \text{ c. ft.} \times 62 \cdot 2 \text{ lbs.} \times 43 \cdot 38^\circ \times 772}{30' \times 33{,}000}$$
$$= 20 \cdot 52 \text{ horse-power,}$$

3rd, and finally, a certain amount of loss by radiation, convection, and leakage, amounting to ·47 horse-power.

Dr. BALANCE-SHEET OF GAS-ENGINE. *Cr.*

	Horse-power.		Horse-power.	Per cent.
Available power .	29·49	Indicated power . .	8·5	28·83
		Carried off by water-jacket	20·52	69·58
		Loss by radiation, &c. .	·47	1·59
	29·49		29·49	100·00

The water-jacket, which is an unfortunate mechanical necessity in consequence of there being, at present, no other known method of keeping the working parts in a state of efficiency at high temperatures, consumes nearly 2½ times as much heat as the useful work given out. The practical efficiency of this particular engine was only 8½ horse-power out of a total of 50·53 possible if the products could have been cooled to absolute zero; this realised, therefore, only 17 per cent. of the energy latent in the gas.

With good gas, it is said that the larger engines consume only 21 cubic feet per indicated horse-power per hour; a reference to the table of "Properties of Fuels" (page 99), tells us that 1,000 cubic feet of good gas will yield 617,485 units of heat, hence 21 cubic feet per hour should yield per minute $\frac{617{,}485^{u} \times 21 \text{ c. ft.} \times 772'}{1{,}000 \text{ c. ft.} \times 60' \times 33{,}000} = 5 \cdot 056$ horse-

power capable of producing only 1 horse-power, so that even good gas will only yield a duty of 20 per cent. Carnot's theory enables us to give a reason for this result. First, the initial temperature cannot be raised to the highest point possible; and, secondly, the terminal temperature is excessively high. In addition, there is the terrible waste in the water-jackets. The theory we have been considering indicates that a higher range of duty is attainable, and we may be sure that the time will come when, by suitable mechanical contrivances, better results will be obtained. One method of improving the economy, though not the efficiency, of gas-engines, is to use crude gas, generated in a producer somewhat on Siemens' system. By this means, nearly the whole of the coal is converted into various gases, and is used at once in the engine. The table of the properties of fuels tells us that Wigan coal, for example, produces 14,051 units of heat per 1 lb. of coal. If consumed in an hour this would yield

$$= \frac{14{,}052^{u} \times 772}{60 \times 33{,}000} = 5 \cdot 48 \text{ horse-power, and at 20 per}$$

cent. duty should give $1 \cdot 1$ horse-power. As a matter of fact, 1 lb. of coal applied in this way, on a large scale, is yielding seven-tenths of a horse-power. With all its imperfections, however, the gas-engine has taken a firm place as a trustworthy, safe, convenient and even economical contrivance for the conversion of heat into useful work.

HOT-AIR ENGINE. (FIG. 44.)

We now come to the investigation of the properties of hot air as an agent in the conversion of heat into work.

Air, being a mixture of gases which do not alter their physical properties through a wide range of temperature

and pressure, is peculiarly fitted for illustrating the theoretical aspects of the subject before us. The specific heat of air, at constant volume, when the increase of its temperature is unaccompanied by the performance of external work, is ·169. The pressure of a given volume of air, when heated, increases as its absolute temperature, if there be no change of volume, and, at first sight, it would appear that if air were heated in a confined space and then allowed to expand, doing external work, that the whole of the heat imparted could be converted into work, and the air rejected at the normal temperature and pressure of the atmosphere. If this could be done, a perfect engine would be the result; but the fall of temperature in air, when used as a working agent, does not keep pace with the fall of pressure.

On the diagram (Fig. 43), are represented the relations between the volume, pressure, and temperature, of say ten cubic feet of air at 40° Fahr. or 500° absolute, and at one atmosphere absolute pressure, that is, at the ordinary pressure which surrounds us. The base line represents absolute zero of temperature, and forms the abscissæ of the curves.

The vertical lines represent absolute temperatures. The diagonal line, A, drawn from the point where 500° and one atmosphere intersect, to 5,000° at ten atmospheres, represents the increase of temperature required to produce any given pressure, and is the graphic representation of the equation—

$$T_1 = \frac{T\,P_1}{P}$$

The curved dotted line, B, defines the temperatures to which the air will fall when expanding from any given pressure down to one atmosphere while doing external

work. The equation from which these temperatures are calculated is—

$$T_1 = \frac{T}{\left(\frac{P}{P_1}\right)^{\cdot 29}}$$

If these calculations be correct, then the work done in expanding must correspond with the energy latent in the number of units of heat which have disappeared. Take the case where, by heating the air to 2,000°, a pressure of

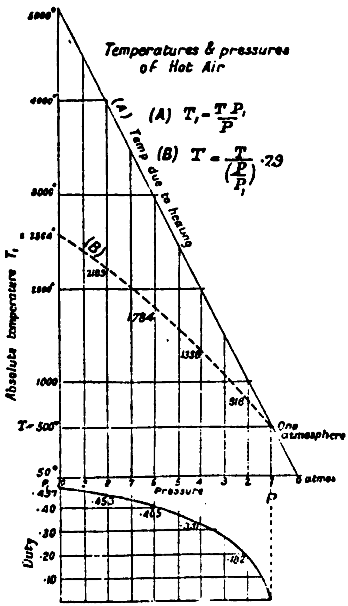


Fig. 43.

four atmospheres is attained. On expanding and doing work, the temperature will fall 662°, or down to 1,338° absolute. The weight of ten cubic feet of air at 500° and one atmosphere is ·7944 lb.; hence the energy which has

been changed into motion is $= 662° \times \cdot 7944$ lb. $\times \cdot 169 \times 772' = 68{,}611$ foot-pounds.

The work done in expanding along the adiabatic curve is—

$$= \frac{10 \text{ c. ft.} \times 2{,}116 \cdot 8 \text{ lbs.} \times 4 \text{ at.}}{\cdot 408} \left\{ 1 - \left(\tfrac{1}{4}\right)^{\cdot 29} \right\} = \cdot 68 \cdot 693 \text{ foot lbs.}$$

The value 2,116·8 lbs. is the pressure of one atmosphere in pounds per square foot. The two results are practically identical, and hence, because the energy in the air is proportional to its temperature, the triangle bounded by the diagonal line, A, will represent the total potential energy of the air at various temperatures and pressures, while the curve, B, shows how much is capable of being rendered kinetic; the ratio, in any ordinate, of the piece between the dotted and the full lines to its total length represents the proportion of heat which can be utilised, and is in effect Carnot's function.

$$\frac{T - t}{T.}$$

The curve beneath the upper figure indicates how rapidly the possible duty diminishes with the decrease of temperature. At four atmospheres the duty can only be 33 per cent., yet under these disadvantageous circumstances a horse-power could, theoretically, be produced for a little more than half a pound of coke per hour.

Referring to the fuel table, we find that one pound of coke yields 13,640 units of heat. By suitable arrangements it can be used to heat air so that the waste products shall escape at about 800° absolute; taking 4,000° as the maximum temperature of the fire, we may expect to realise $\frac{4{,}000° - 800°}{4{,}000°} = \cdot 80$, and, therefore, counting from abso-

lute zero, the available heat will be = (13,640" + 500° × ·169) × ·8 = 10,978 units.

The air has been heated from 500° to 2,000° absorbing 1,500° × ·7944 lb. × ·169 = 201·4 units at the expense of $\frac{201 \cdot 4}{10,978} = 0 \cdot 0184$ lb. of coke. If the work done by this heat be performed in one minute, it would indicate $\frac{68,693 \text{ foot-pounds}}{33,000 \text{ foot-pounds}} = 2 \cdot 08$ horse-power. The coke consumed per hour would be ·0184 × 60 = 1·104 lbs., and, therefore, the coke consumed per horse-power per hour would be $\frac{1 \cdot 104 \text{ lbs.}}{2 \cdot 08 \text{ h.-p.}} = \cdot 53$ lb.

Again, in this particular case, out of the total 2,000°, only 662° have been utilised; there remains 838° available before the exhausted air sinks in temperature to that of the surrounding atmosphere. Can no use be made of this heat? An answer was given to this question by Stirling, at the beginning of this century, when he invented the regenerator, which has since become widely known in connection with other heat-appliances. In hot-air engines the regenerator consists of a number of metal plates, tubes, or sheets of gauze, through which the air passes to and fro; the hot air, in passing through, heats the metal, and the cold air, in returning, is, in its turn, heated by the hot plates, the zone of heat oscillating backwards and forwards with the air.

One of the most successful of the hot-air engines is known as the Rider engine, manufactured by Messrs. Hayward, Tyler, and Co. (Fig. 44.) The engine consists of two plungers, C and D, coupled by means of connecting rods to cranks keyed at right angles to each other on a crank shaft common to both; one plunger, D, called the power plunger,

works in a cylinder kept permanently hot by means of a fire, while the other, C, called the compression plunger, works in a cylinder surrounded by a water-jacket. The two cylinders are connected by a wide passage, H, filled

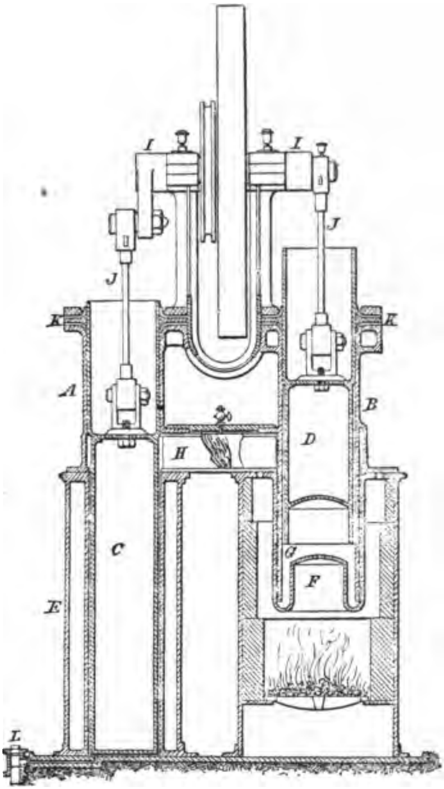


Fig. 44.

with plates, and constituting the regenerator. There is no change of air in this engine, but the relative motions of the two plungers cause a constant variation in volume, and

an interchange of air between the two cylinders, the increasing volume on the forward stroke synchronizes with an increase of the heating power, because most of the air is in the hot cylinder, while the decreasing volume in the "in" stroke is provided for by the preponderance of cooling power, because most of the air is in the cold, water-jacketed cylinder. The power plunger, D, has the lead of the compression plunger by a quarter of a revolution. Suppose it to have completed half its upward stroke, as on the diagram, the compression plunger being right down, most of the air, considerably compressed, is on the hot side and is being rapidly heated and expanded. The consequent pressure impels the power plunger, D, outward, and, being transmitted through the regenerator, H, acts on the compression plunger, C, whose crank has just turned its bottom centre; both plungers now move upward and drive the crank shaft. By the time the power plunger, D, has reached the top of its stroke, a considerable volume of air has passed through the regenerator, been cooled by it, and filled half the compression cylinder, C, where its temperature is further lowered by the water-jacket, E. The momentum of the fly-wheel, aided by the pressure in the compression cylinder, C, now carries the power plunger down against the pressure, but by so doing reduces the volume of air exposed to the fire, and increases that subjected to the cooling influence, so that the balance is against the fire.

By the time the power plunger, D, has descended half its stroke, the compression plunger also begins to descend, and to compress the cold air under it, and drive it backwards through the regenerator, H, from which it takes up the heat into the power cylinder, D, where it gets further warmed, till the power plunger again begins to ascend, and

attains the half-stroke, so completing the cycle. The supply of air, to make up for leakage, is derived from a small inlet pipe, L, attached to the bottom of the compression cylinder, and fitted with an automatic valve opening inwards. At the turn of the stroke, if there be any deficiency of air, a partial vacuum is formed, which causes a fresh supply to rush in. There are no distributing valves in this engine, and each plunger works through a leather packed gland, K, which, in the case of the power plunger, is kept cool by a water-collar immediately under it.

The power cylinder is surrounded, for about half its lower length, by an iron jacket, F, around which the fire plays, the air passes backwards and forwards through the annular space between the cylinder and the jacket, and by that means is not only heated itself, but prevents an excess of heat reaching the cylinder. The regenerator is filled with cast-iron plates about $\frac{1}{8}$ inch thick, placed $\frac{1}{32}$ inch apart. The speed varies from 100 to 140 revolutions per minute. No satisfactory data as to temperature are to be obtained; the air is probably heated to the dull-red heat of cast-iron, which may be taken at 1000° Fahr. The water-jacket, as in the gas-engine, carries off a good deal of heat, which is, therefore, incapable of being converted into useful work. There is a great variety of hot-air engines, and though extremely useful for small powers, the whole class is not of sufficient importance to claim more of our attention.

Compressed Air Refrigerating Machines.

(Figs. 45, 46, 47.)

In the compressed air refrigerating machines we have an interesting example, first, of the conversion of heat into work through the agency of steam; next, the development

of heat, by the energy so obtained being employed to compress air; and finally, the absorption of heat by the compressed air being made to do work in its turn. Through

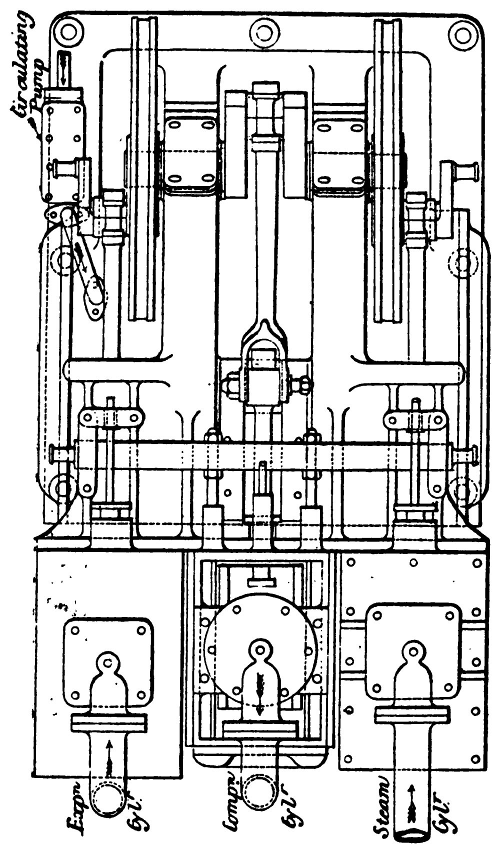


FIG. 45.

the kindness of Mr. Hesketh, the senior representative of the old house of J. & E. Hall, of Dartford, Figs. 45, 46, 47,

have been prepared from drawings of one of their refrigerating engines, to which three gold medals were awarded at the Health Exhibition.

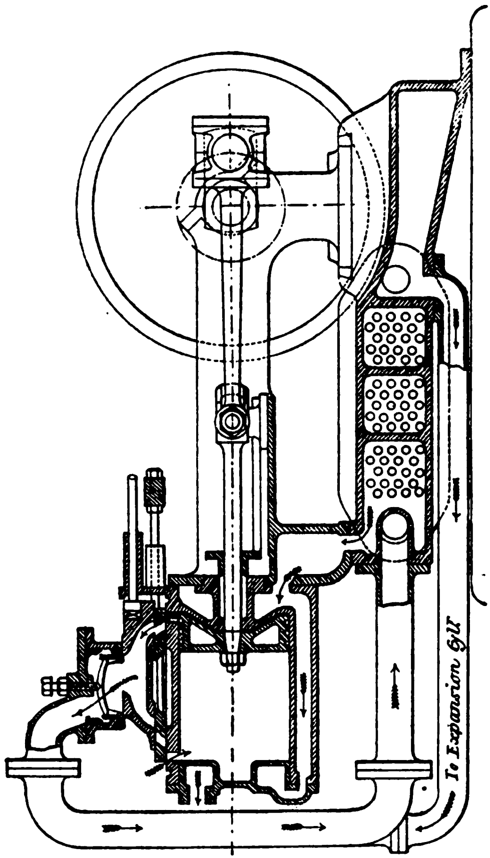


FIG. 46.

The machine consists of three cylinders, fitted with metallic pistons, placed side by side, and connected by a

crank-shaft, common to all, by means of piston-rods, cross-heads with slipper guides, and connecting-rods, in the manner common with ordinary horizontal engines. The same crank-shaft drives a water-circulating pump, and beneath the frame, which carries the whole mechanism, is a tubular refrigerator. The left-hand cylinder, Fig. 45, is of the kind ordinarily made for steam-engines, and may be constructed with expansion valves, steam-jacket, and all other accessories suitable for a steam-engine of the best

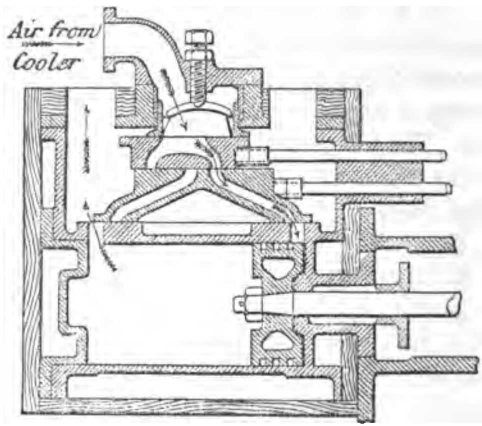


FIG. 47.

construction. The power developed in this cylinder is transmitted through the crank-shaft, by an overhung crank, to an intermediate crank, which actuates the piston of the middle, or air-compressing cylinder, which is water-jacketed, and fitted with double-slide valves, of peculiar construction (Fig. 46) and proportions, through which air is drawn in from the outside atmosphere and delivered, compressed to about 45 pounds per square inch, and at a tem-

perature of about 250° to the tubular refrigerator. The hot air circulates through a number of metal tubes, round the outsides of which passes a current of water supplied by the circulating pump, actuated by the right-hand end of the crank shaft. The water rises about 10° in temperature, and carries off, in the form of heat, a portion of the energy of the steam-engine. The compressed air, reduced to nearly the normal temperature, and at a pressure of 45 lbs. per square inch, next enters the right-hand cylinder on the diagram, through double-slide valves, also of special construction, Fig. 47, and is made to expand, doing work upon the piston, and therefore its temperature falls in proportion to the amount of energy communicated to the crank-shaft, which energy is applied to reduce the work to be done by the steam. The temperature of the air is reduced by this means to as much as 130° below the freezing point. In some cases, instead of drawing air into the compression cylinder from the atmosphere, it is drawn from the refrigerated chambers, and is made to pass over a number of tubes containing the compressed air, which is thus cooled to a still lower temperature than was effected by the cooling water, the result being that a relatively lower temperature is obtained after expansion. Simple as the process appears to be, yet, to obtain the best results, great nicety is required in the proportions of the cylinders, in the extent to which the air is compressed, the degree to which the air is expanded, and in the practical details of the valve gear, which are especially important with respect to the difficulties attendant upon the formation of snow and ice derived from the freezing of the moisture always contained in the air. It is the successful treatment of these details which makes the difference between an economical and trustworthy machine and a wasteful or uncertain one.

When applied to refrigerate the holds of vessels engaged in the dead meat trade, the money value depending on the efficiency and trustworthiness of a machine, is very large.

Setting aside friction, the power necessary to drive the circulating pump, and the heat represented by radiation and conduction, the useful work done by the steam is measured by the quantity of heat carried off by the water circulating round the cooling tubes and the compression cylinder. The theoretical amount of cooling is easily determined.

The air under an absolute pressure of four atmospheres, and at a temperature a little above that of the surrounding atmosphere, say at 60°, is expanded along the adiabatic curve to one atmosphere, the absolute temperature at the end of the operation will therefore be—

$$\frac{520^\circ}{\left(\frac{4}{1}\right)^{\cdot 29}} = 348^\circ \text{ absolute,}$$

which is 144° below the freezing point. The temperature attained in practice is about 130° below the freezing point, the air, in expanding, absorbs a certain amount of heat from the cylinder, and hence the slight discrepancy.

The Steam Boiler.

The last agent in the conversion of heat into useful work which we have to examine is steam, the most important of all, and at the same time the most difficult to investigate exactly. The peculiarity of steam is that, at ordinary temperatures and pressures, it is in the liquid form, and is not capable of being used as a working substance. Hence, the

application of it must be considered under two heads—first, the conversion of the liquid into an elastic gas; and secondly, the application of the gas, so obtained, to produce work by means of heat-engines. The two operations, though perfectly distinct, are very often confounded together, and the efficiency of the steam-engine is mixed up with that of the fuel and of the boiler.

Water, from which steam is derived, is a substance endowed with a higher specific heat than any other body; that is to say, it requires more heat to raise its temperature one degree. The British unit of heat, as already explained,

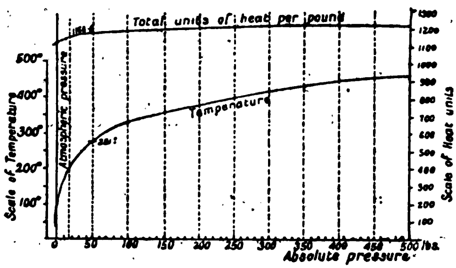


FIG. 48.

is defined to be the quantity of heat which will raise one pound of water at the freezing point 1° Fahr. Steam also has a higher specific heat than most gases, being ·370 at constant volume, and, consequently, the value of γ, the ratio of specific heat at constant pressure to that at constant volume is lower, being 1·3, which means that the heat absorbed in the work of expansion bears a smaller proportion to the total heat required to produce a change of temperature, than is the case with air, for example, of which the true specific heat is only ·169.

The diagram (Fig. 48) represents, in a graphic manner

the properties of steam, from 0 to 500 lbs. pressure per square inch. The base line is divided into equal parts, and represents the absolute pressures, that is to say, the pressures reckoned from a perfect vacuum.

The ordinates bounded by the inner curve represent the temperatures, corresponding to the pressures, according to a scale on the left side of the figure. It should be noticed that the temperatures rise rapidly from absolute vacuum to about 50 lbs. pressure, after which the rise is much more gradual.

The ordinates defined by the upper curve represent according to the scale on the right-hand side, at any given pressure, the total units of heat contained in the steam and the water from which it is derived, the latter taken at the freezing point. The curve has been calculated by Regnault's formula, according to which the total heat in a pound of saturated steam

$$= 1091 \cdot 7^\circ + \cdot 305(t^\circ - 32^\circ),$$

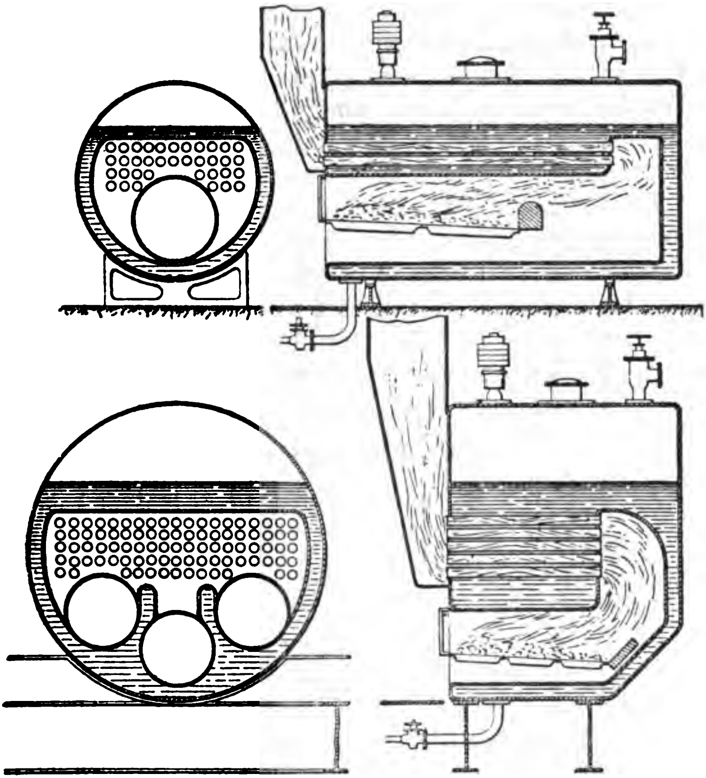
where $1091 \cdot 7^\circ$ F. is the total heat of vapour at the freezing point and t° is the temperature of the steam in degrees F. The relations between the pressure, temperature and weight of steam are given in most Engineers' Pocket Books and in Rankines' "Rules and Tables."

If, for example, we wished to know how many units of heat would have to be communicated to a pound of water, at 50°, to produce steam at 35 lbs. above the atmosphere, we find from the diagram Fig. 48 that, corresponding to 50 lbs., which is the absolute pressure of the steam, we have a temperature of 281° and 1,167·6 units of heat, reckoned from 32, therefore deducting (50—32) = 18°, gives 1,149·6 units, the quantity required.

The apparatus in which water is converted into steam is

called a steam boiler or generator, and has now assumed certain well-defined forms.

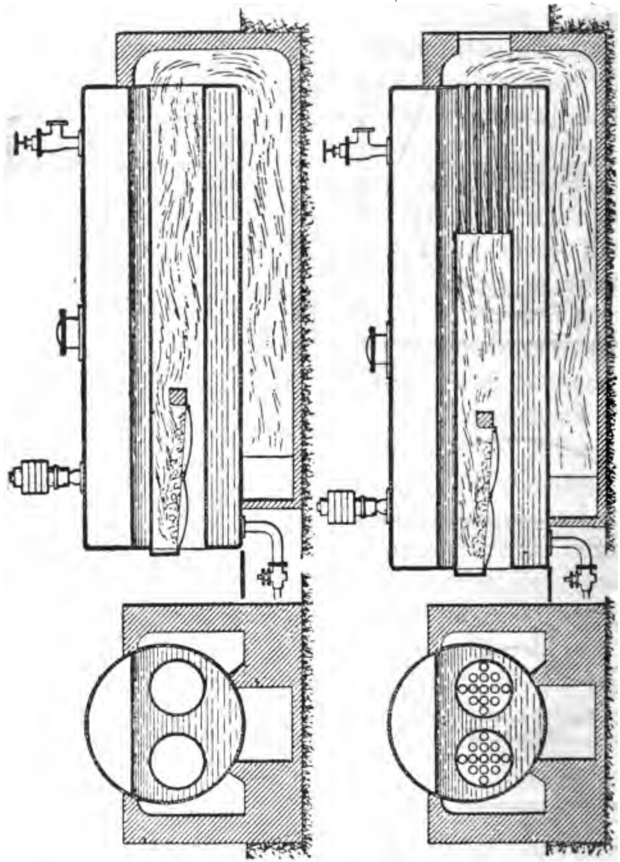
For portable purposes, such as are required on railways



FIGS. 49, 50.

in agricultural and traction engines, the familiar locomotive type (Fig. 53) is invariably adopted. It consists of a rectangular firebox, surrounded by a narrow water space attached to one end of a cylindrical shell, the opposite end

of which terminates in a tube plate, which is connected to the fire-box by numerous small tubes, the outer ends of

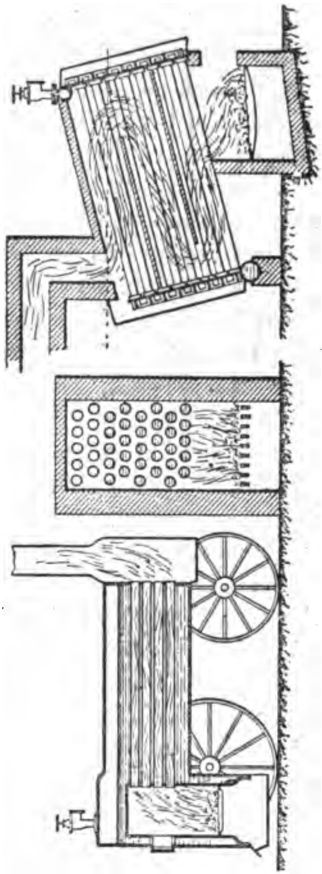


Figs. 51, 52.

which terminate in a smoke-box, surmounted by a chimney.

For marine purposes, a cylindrical shell (Figs. 49, 50),

of which the diameter and length are nearly the same, is fitted with from one to three furnace flues, terminating in a combustion chamber, which is placed close to the rear end of the boiler. This chamber is carried vertically higher than the flues, and is connected, over the flues, with the front end by numerous small tubes which terminate in a smoke-box, which is attached to the front of the boiler and is surmounted by a chimney.



FIGS. 53, 54.

For stationary purposes (Figs. 51, 52), the shell is generally cylindrical, the length being much greater than the diameter. Each shell contains one or two cylindrical flues, the front ends of which form the furnaces. The flues are commonly traversed by water pipes, and sometimes terminate in clusters of small tubes. The shells are usually set in brickwork, and the products of combustion are carried round and beneath them before being consigned to the chimney. For small powers, vertical boilers of innumerable forms are em-

ployed; and sectional boilers (Fig. 54), composed of small pipes set in ovens, are not uncommon.

Of whatever form a boiler may be, it is essential for its efficiency that combustion should take place in a furnace of large volume, so that the temperature of the flame may be maintained so long as chemical action is proceeding; and that the proportion between the quantity of heat developed in the furnace, and the area of the surface which is destined to absorb the heat, should be such that the products of combustion should be finally rejected at as low a temperature as practicable; and that the fall of temperature should be caused by the useful work being done—that is to say, by the heating of the water fed in, and by the conversion of that water, when it has reached the proper temperature, into steam. The useless work consists in the heating of the rejected products of combustion, and the warming of the air and objects around the boiler, by convection and radiation. When these conditions are observed, the application of Carnot's principles shows that there is very little scope for the improvement of steam boilers.

An excellent illustration is afforded in the case of a vertical boiler, which was very carefully tested by Sir Frederick Bramwell and Dr. Russell, some ten years ago, and it may here be mentioned that the method of representing by means of a balance sheet, the relations between the power available and the manner in which it is expended was first employed by Sir Frederick Bramwell with reference to this experiment. The fuel used was coke and wood, the composition, both of the fuel and of the products of combustion, was ascertained by analysis, the quantity of air and feed-water used and their temperatures were ascertained, and the loss of heat by radiation

was determined, so that, in this remarkable case, we have the means of calculating accurately the values on both sides of the account.

The facts observed were as follows:—

Steam pressure 53 lbs.	= 300·6° F.
	lbs.
Fuel—Water in coke and wood	26·08
Ash	10·53
Hydrogen, oxygen, nitrogen, and sulphur	7·18
Total non-combustible	43·79
Carbon, being useful combustible	194·46
Total fuel	238·25
Air per pound of carbon	17⅛ lbs.
Time of experiment	4 h. 12 min.
Water evaporated from 60° into steam at 53 lbs. pressure	1,620 lbs.
Heat lost by radiation and convection	70,430 units.
Mean temperature of chimney	700° F.
" " air	70° F.

No combustible gas was found in the chimney.

The total potential energy of the fuel with reference to absolute zero, the temperature of the air being 70°, was:—

	Units.
238·25 lbs. fuel × 530° × ·238	30,053
194·46 lbs. carbon × 17⅛ lbs. air × 530° × ·238 = absolute heat in air	420,060
194·46 lbs. × 14,544[*] combustion of carbon	2,828,200
Total energy	3,278,313
Heat absorbed in evaporating 26·08 lbs. of water in the fuel	29,888
Available energy	3,248,425

Temperature of Furnace.—The heat of combustion was 2,828,200 units, but of these 29,888 units were absorbed in evaporating 26·08 lbs. of moisture in the fuel, leaving thus, 2,798,312 units available from 238·25 pounds of combustible = 11,745 units per pound.

$$\text{Absolute temperature} = \frac{11{,}745^{\bullet}}{18 \cdot 125 \text{ lbs.} \times \cdot 238} + 530^{\circ} = 3{,}253^{\circ}$$

$$\text{Absolute temperature of products } 700^{\circ} + 460 = 1{,}160^{\circ}$$

$$\text{Maximum duty} = \frac{3{,}253^{\circ} - 1{,}160}{3{,}253^{\circ}} = \cdot 643$$

$$\text{Maximum work} = 3{,}248{,}425 \times \cdot 643 = 2{,}101{,}700^{\bullet}$$

The useful work done was the evaporation of 1,620 lbs. of water from 60° at 53 lbs. pressure, which represented 1,855,900 units, the work of displacing the atmosphere by the smoke amounting to 147,720 units, the loss by radiation and convection was ascertained to be 70,430 units, and the heat left in the ashes is estimated at 1,129 units. Arranging these data in the form of a balance-sheet, we see that only 26,521 units of heat are not accounted for.

Dr. BALANCE-SHEET OF BOILER. *Cr.*

	Units.		Units.	Per cent.
Available heat.	2,101,700	1,620 lbs. of water evaporated .	1,855,900	88·29
		Displacing atmosphere . . .	147,720	7·03
		Loss by radiation and convection	70,430	3·35
		Heat left in ash	1,129	·05
		Unaccounted for	26,521	1·26
	2,101,700		2,101,700	100·

On the right hand side of the balance-sheet is placed a column, indicating the percentage which each of the items bears to the total. The large proportion of energy, amounting to over 88 per cent., converted into useful work is very striking, and the next considerable item is the displacement of the atmosphere, which absorbs 7 per cent. The quantity unaccounted for is only 1¼ per cent., which demonstrates the skill and care brought to bear on this experiment.

The doctrine of Carnot requires that, in order to get the

best duty out of fuel in steam boilers, the range of temperature between the furnace and the chimney should be as great as possible; the temperature of the furnace must, therefore, be raised to the utmost, while that of the chimney must be lowered as much as possible. The tables of the properties of fuels in the fourth chapter give the quantity of air theoretically necessary to produce perfect combustion, and, could the fuel be consumed under such circumstances, the highest temperature of furnace attainable would be reached. This can, indeed, be done with dust fuel, petroleum or gas, but in ordinary cases with lump fuel, owing to the imperfect mixture of the elements, a large excess of air must be admitted, with the consequent effect of reducing the temperature of the furnace by the amount to which the excess of air has to be heated. Thus, the lowering of the initial temperature being due to the excess of air, the cause of the consequent fall of efficiency admits of a commonsense explanation, for the heat which would, by being retained, have raised the initial temperature is carried off unprofitably by the excess of air.

When extremely energetic combustion takes place in boilers, especially when using water charged with mineral matter which deposits a hard scale or a fine mud, the furnace plates should be protected from immediate contact with the flame in the zone of most intense combustion, because the boiler plates are not able to transmit the heat fast enough to prevent the surfaces next the fuel from becoming overheated, in consequence of which internal strains are set up in the plates and they are gradually destroyed. Refractory brick linings can be used in many cases with advantage, but if the heat be as intense as it should be, even these melt away very quickly,

so that, in practice, there are great difficulties in the way of raising the temperature of the furnace to the utmost.

The temperature of the products of combustion escaping up the chimney is very commonly much too high, and represents serious loss. This is generally inevitable, because a sufficient draught can only be produced by the column of gases in the chimney being highly heated in order to reduce its weight, and by that means disturb as much as possible the balance which would otherwise exist with the air outside. Suppose, for example, a chimney 100 feet high with a temperature of 920° absolute, while the atmosphere was at 520°, and suppose, for simplicity, that the products of combustion in the chimney were all, at the standard temperature, of the same specific density as air. The weight of a column of the atmosphere one foot square 100 feet high would be $= \frac{100 \text{ c. ft.} \times \cdot 0807 \text{ lb.} \times 492^\circ}{520^\circ} = 7 \cdot 635$ lbs. The weight of the heat products in the chimney would be $= \frac{100 \text{ c. ft.} \times \cdot 0807 \text{ lb.} \times 492^\circ}{920^\circ} = 4 \cdot 316$ lbs. so that the column in the chimney would have $3 \cdot 319$ lbs. less weight than that outside it; this difference if expressed in the usual way, in the height of a column of water, would be

$$\frac{12 \text{ inch.} \times 3 \cdot 319 \text{ lbs.}}{62 \cdot 2 \text{ lbs.}} = \cdot 64 \text{ inch.}$$

a little more than six-tenths of an inch draught, which, in practice, is found to be very efficient.

In the fourth chapter we have investigated the economy to be derived from forced draught, that is, from the air being pumped into the furnace or drawn out of the chimney by mechanical means, instead of by the pressure

due to the heated gases in the chimney. The benefits which can be derived, however, are conditional upon the gases being cooled, before they are finally rejected, by doing useful work such as heating the water being fed into the boiler, and this must be done by apparatus detached from the boiler and working at a lower temperature than it. The ordinary working pressure of a locomotive is 250 lbs. per square inch; of a marine boiler 150 lbs., and of a land boiler 100 lbs. The temperatures corresponding to these pressures are 406°, 364°, and 340° respectively. But the products of combustion should not be allowed to escape at more than 50° above the atmospheric temperature, so that obviously the cooling cannot be effected by any mere extension of the boiler. The best arrangement, that which has been widely adopted for land boilers, is an apparatus known as "Green's Economiser." It consists of several rows of vertical tubes placed in a chamber formed in the flue which connects the boilers with the chimney. The tubes are connected together at their upper and lower ends, and in such wise that the feed water, which is introduced cold into the tubes nearest the chimney, travels slowly through the economiser to its boiler end, by which arrangement the hotter gases come in contact with the hottest water, and the cooled products with the cold feed. To prevent an incrustation of soot forming on the tubes, and so injuring their thermal conductivity, each tube is encircled by a scraper; a number of scrapers are connected in groups and are moved slowly up and down by automatic mechanism driven by a small steam engine or other convenient source of power. The number of tubes used depends, of course, upon the power of the boilers. The unfortunate circumstance connected with this method of cooling the products of combustion is that the weight and

bulk of the apparatus preclude its being used on locomotives or on board of steam vessels, the very places where forced blast is most commonly and easily applied; for in locomotives, their speed through the air as well as the exhaust-steam create a fierce blast, while the structure of steamers lends itself admirably to making air-tight stoke-holes, in which a pressure of air can be maintained by means of an ordinary fan blower.

Forced draught is being used to a considerable extent in torpedo boats and war ships, but the object there is totally different from the one we have just been discussing; it is not for the purpose of securing the efficiency of the boiler, but for raising as much steam as possible on an emergency and for a short time. Some attempts are now being made, however, to apply the system to merchant vessels and to land boilers, mainly with the view to the more efficient consumption of small coal; the results attained are encouraging, though difficulty is experienced with the large amount of soot and dust which the strong blast carries over into the flues and even into the air through the chimney.

In the balance-sheet of a boiler the main item on the credit side was the weight of water evaporated. In practice it is not always easy to determine this quantity correctly on account of "priming," or the tendency which exists of a certain quantity of spray or water, in a fine state of subdivision, being carried over by the steam. The amount of priming in a boiler depends upon a great many circumstances, such as the shape of the boiler, the quality of the water, the rate at which the boiler is worked, the manner in which the steam is taken off and the feed introduced.

If a boiler have a small water surface compared with its heating surface, as is usually the case in marine boilers

and locomotives, then the rapid evolution of steam causes violent disturbance of the water surface and augments the chances of spray being carried over, and necessitates the use of separators and special arrangements for getting the steam into the pipes. Some kinds of water again are very troublesome, and cause priming in a capricious manner. In speaking of gunpowder smoke, the laws relating to the motions of small particles in viscous fluids have been dwelt upon; the minute particles of water suspended in the steam also subside gradually as dust does in air, but if the motion of the steam towards the steam-pipe from all parts of the water surface exceeds a certain velocity, the particles have not time to fall, and are carried over by the steam, and the more rapid the motion is, the larger are the particles which are carried over and consequently the more severe the priming.

In discussing the behaviour of air and other gases as agents in the conversion of heat into work, we have assumed that the gaseous condition would be retained down to absolute zero, and that the specific heat and all other properties remained unchanged. This assumption is incorrect, because all gases, like steam, change their physical states under certain conditions of temperature and pressure; but no sensible error has been occasioned by the assumption made, because the working substances remained unchanged within the range of temperature and pressure under consideration. With steam, however, matters are very different. At moderate ranges of temperature and pressure, steam may be either in the liquid or gaseous condition, so that the work done is not necessarily proportional to the fall of temperature.

Take the case of a cubic foot of water converted into steam at 65 lbs. absolute pressure, and the corresponding

temperature of 298°. Imagine this steam let out of a boiler into the air, the pressure would be reduced to 14·7 lbs., the temperature to 212°, and the volume should be increased to 1,642 cubic feet, if it were not for the heat which must be converted into the work of displacing the atmosphere. Could steam expand along the adiabatic curve the temperature would fall to—

$$\text{temperature} = \frac{758^\circ}{\left(\frac{65}{14\cdot7}\right)^{\cdot23}} = 538\cdot5^\circ \text{ absolute,}$$

or to 78° on our ordinary scale, but at that temperature steam would not have the tension due to the pressure of the atmosphere, and would, therefore, be unable to penetrate it.

The chief cause of the fall of temperature is the work done in displacing the air, therefore there must be an equality between the energy necessary to displace the air and that represented by the units of heat absorbed, and as the temperature cannot fall below 212°, the heat required must be obtained from the liquefaction of a portion of the steam. Neglecting the volume of water formed, and supposing x to represent the volume of steam condensed, then $(1{,}642 \text{ c. ft.} - x) \times 2{,}117$ lbs, per square foot = work done in displacing atmosphere.

The temperature of x in condensing falls from 298° to 212°, which from our diagram we find corresponds to 961·8 units of heat per 1 lb. A cube foot of steam at 14·7 lbs. and 212° weighs ·0379 lb., the volume not condensed falls 86° in temperature, so that the foot-pounds of work done represented by the heat liberated by the condensed steam

$$= \left\{(1{,}642 - x) \times \cdot0379 \text{ lb.} \times \cdot305 \times 86^\circ + x \times \cdot0379 \text{ lb.} \times 961\cdot8^u\right\} \times 772^J$$
$$= 767\cdot5\,(1{,}642 - x) + 28{,}112x.$$

this must equal $(1{,}642 - x) \times 2{,}117$, hence—$x = 75 \cdot 2$ c. ft.; that is to say, 75·2 cubic feet of steam will be condensed into water in a very finely divided state, interspersed through the escaping steam, and this water can be plainly seen at the mouth of any pipe discharging steam into the air. But the heat necessary for conversion into the work of displacing the air is not taken from the steam alone, but also from any object it may meet with, hence the hand introduced into a jet of high-pressure steam is not scalded, but when steam issues from the spout of a kettle the circumstances are totally different; the work of displacing the atmosphere is done when the bubbles of steam are formed in the water, and at the expense of the fire, hence the jet of steam maintains its full temperature, and will scald the hand if introduced into it. After the escape of steam from a pipe, it mingles with the surrounding air, and, if the latter be dry and warm, is quickly diffused as invisible vapour, but if cold, and already saturated, is condensed into small globules, which are so numerous, as to form the dense white clouds with which we are so familiar.

The Injector.

The simplest form of steam engine is the injector (Fig. 55). It consists of a mechanical arrangement, by which a jet of steam is made to mingle with a stream of water which it warms in being itself condensed, after which the current of steam and water is delivered to a height, or under a pressure, depending upon the tension of the steam and the proportion of water mingled with it.

The apparatus in its most complete form is illustrated by the diagram fig. 55. Steam enters through a pipe A communicating with a nozzle, the orifice of which can be

opened or closed by a taper spindle D, which is made adjustable by a screw and handle E. The nozzle itself

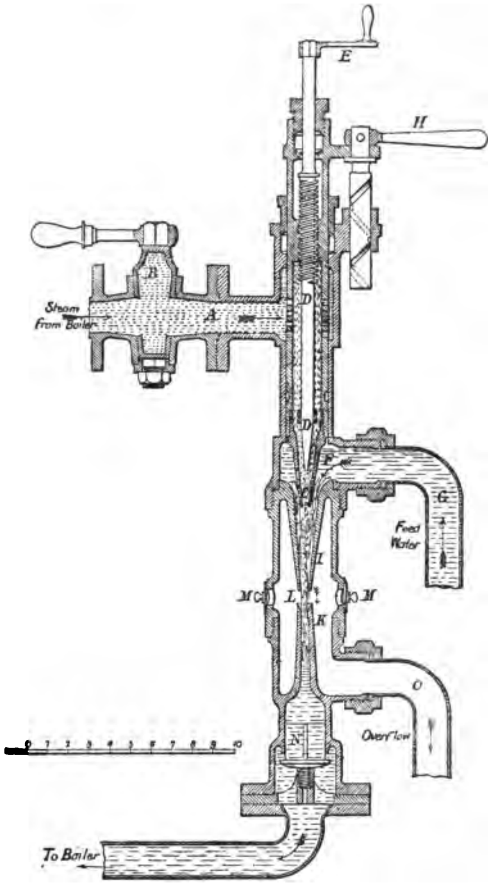


FIG. 55.

enters a fixed outer nozzle F also of conoidal shape, and which can be moved longitudinally by the handle H, so as to

vary the area of the annular space between itself and the fixed cone I, the latter being connected at its upper end, by a branch pipe G to the water supply. The outer end of the fixed cone terminates in a chamber L connected with the atmosphere by the peep-holes, M, and, opposed to it, is a second fixed cone K, enlarging in the opposite direction. The outer end of this cone is guarded by a self-acting valve N, opening outwards, and is connected to the delivery pipe. When steam is admitted through its nozzle, the jet issues into the fixed cone; and because this is of larger area, its velocity is reduced, and a certain amount of kinetic energy is rendered potential, just as we saw in the case of diverging pipes. The potential energy takes the form of a reduction of pressure in the water chamber at F, which at once causes water to flow and surround the steam jet, which is immediately condensed, the water is raised some 60° in temperature, the velocity of the combined stream of condensed steam and water is reduced in proportion to the increase of weight, and enters the second cone, where the velocity is still further gradually reduced by the diverging pipe, and its potential energy increased to such an extent that the liquid stream will rise to a pressure considerably greater than that of the boiler which supplied the steam.

Let us take a particular case. The No. 8 injector has a steam jet 8 millimetres or ·32 inch in diameter, and is the size usually supplied to locomotives. The feed water rises about 60° in temperature. We will assume steam at 100 lbs. absolute pressure, and 328° temperature. The velocity with which steam, under these conditions, will discharge into the air, is about 2,593 feet per second, and the weight delivered will be ·0549 lb. in the same time. Suppose the feed water at 50°, then the

mixture of steam and water will be at 110°, the water rising 60° and the steam falling in temperature 218°. The total heat of steam, at 100 lbs. per square inch, above 110° is 1104 units; therefore if x be the weight of water injected per second, the number of units of heat absorbed in being heated 60° will be 60 x; therefore 60 $x = 1104 \times$ $\cdot 0549$ lb., whence $x = 1 \cdot 01$ lbs., and the weight of the combined steam will be $1 \cdot 01 + \cdot 0549 = 1 \cdot 065$ lbs. per second, and consequently the velocity will be reduced to $\frac{\cdot 0549 \times 2{,}593}{1 \cdot 065} = 133 \cdot 6$ feet per second, and its kinetic energy will be $\frac{1 \cdot 065 \text{ lbs.} \times 133 \cdot 6^2 \text{ feet}}{64 \cdot 4} = 295 \cdot 5$ foot-pounds.

The stream, endowed with this energy, occupies much less space than the jet of steam, and therefore the throat of the receiving cone is reduced in diameter, and should, in this case, have an area of ·0184 square inch and a diameter of ·153 inch only. The delivery pipe of the apparatus is about $1\frac{1}{2}''$ diameter, or 96 times the area of the throat, so that the velocity of the water will fall to 1·39 feet per second, and its kinetic energy to ·032 foot-pound, leaving 295·47 foot-pounds available for overcoming the pressure against which the water has to be discharged. The area of the pipe being 1·76 sq. in., and velocity in it 1·39 feet per second, this energy would be absorbed if the water were discharged under a pressure of 120·1 pounds per square inch above the atmosphere or 134·8 lbs. absolute, so that an injector is competent to raise water to a considerably greater height, or deliver it under a greater pressure, than that of the steam which actuates it.

In this investigation no allowance has been made for

friction, eddies, fluid contraction at the orifices, or loss of heat externally; these make an appreciable difference in the calculations, yet results quite as high as here indicated have been obtained. By reducing the proportion of water to the utmost, its temperature is raised, and its velocity, and therefore the kinetic energy of the combined current, is increased to such a point that one boiler has been made to feed another, working under twice the steam pressure.

CHAPTER VII.

THE apparatus which is commonly called a steam-engine consists essentially of a vessel of cylindrical or spherical form, in which a piston works steam-tight, and receives from a boiler a supply of steam which pushes the piston either backwards and forwards, or round, in a continuous manner.

Steam-engines may be divided into four classes. One in which a piston reciprocates longitudinally in a cylinder and receives the impulse of the steam on one side only, or alternately on both sides; second, where the piston reciprocates about the longitudinal axis of the cylinder; thirdly, into the whole class of rotary engines, in which the motion of the piston is more or less continuous; and lastly into reaction wheels analogous in their action to water turbines.

Reciprocating engines may be single or double acting, and have vertical, horizontal, or inclined cylinders; but in all cases the pistons work steam-tight longitudinally in truly bored cylinders, and transmit the energy imparted to them—by piston-rods working through packed glands in the cylinder covers—more or less directly to the work which has to be performed. The distribution of steam is managed by valves of various forms, actuated automatically by an endless variety of motions; but in all cases steam is admitted at the commencement of a stroke, allowed to

flow in for some portion of it, then shut off and permitted to expand. When the end of the stroke is nearly reached, a passage is opened, by means of which the imprisoned steam is allowed to escape either into the air or into a condenser. In the latter case, it is cooled down, by means of a current of water, to as low a temperature as possible.

Steam cylinders are sometimes surrounded by jackets, the spaces between which and the inner linings are filled with steam at the boiler pressure, and sometimes they are not so constructed, but merely covered, more or less completely, with some non-conducting material.

Fig. 56 is an illustration of a single cylinder, horizontal, expansive condensing engine. *a* is the cylinder, surrounded by the steam jacket *b*. Fitted to slide up and down steam-tight is the piston *c*, with its piston rod *d*, working steam-tight through the stuffing-box or gland *e*, and keyed to the crosshead *f*, the ends of which are supported in slides *g*, *g*. The crosshead is united with the crank pin *h* by means of the connecting rod *i*. The crank pin is fitted into a crank disc which is so formed as to balance the weight of the connecting rod and pin, and is securely keyed on to the crank shaft *j*, which revolves in the bearings *k*, *k*, and carries the fly-wheel *l*, as well as any driving wheels or pulleys that may be needed to transmit the motion of the engine. Steam enters the steam-chest *m*, by means of the pipe and regulating cock *n*, and is distributed by means of the double slide valve *o*, *p*, the steam-passages *q*, and the exhaust port *r* and exhaust pipe *s*. The slide valves are actuated by two eccentrics *t*, *u*, which are secured on the crank shaft, and give to the valves a reciprocating motion, exactly similar, though of much less range, to the motion of the piston *c*, because an eccentric is really a crank with the pin made so large in diameter as to surround the shaft

it is keyed on. The eccentrics are so placed on the crank shaft with relation to the crank, that the main slide valve *o* is travelling in the same direction as the piston at the commencement of each stroke, and the ports through the slide, *v*, *v*, commence to open a way for the steam a little before the piston attains the end of the previous stroke; the steam entering the cylinder thus opposes the motion of the piston for a very short space. This disposition is called the "lead," and serves to arrest the motion of the reciprocating parts with the object described in Chapter I. While the steam is entering on one side of the piston, the spent or exhaust steam is escaping from the other side by the passage *q*, the hollow space *w* in the slide valve, the exhaust port *r*, and so, by the exhaust pipe *s*, either into the air, in the case of a non-condensing engine, or, as in this particular engine, into the condenser. The "expansion" or "cut-off" valve *p* consists of two separate plates connected together by a valve spindle *x*, on the end of which is cut a right- and a left-handed screw working in nuts secured loosely to the valve plates. The valve spindle can be turned round by the tangent screw and handle *y*, and by doing so the two valve plates can be made to approach or recede from each other. The valve spindle has a reciprocating motion communicated to it by the eccentric *u*, which is so set on the crank shaft, that the motion of the cut-off valve is, at the time of cutting off the steam, in the opposite direction to that of the main valve; so that while one of the valve ports *v* is still open to the passage *q*, the cut-off plate slides over the port and so cuts off the steam. The wider apart the cut-off valve plates are, the earlier in the stroke is the steam cut off, and vice-versâ. The piston cannot be allowed to travel the whole length of the cylinder; a space of about $\frac{3}{8}$ inch must be left at each

end, to allow for the spring of the machinery, for unequal expansion, for water which sometimes finds its way in consequence of the priming of the boiler; and this space, together with the passages from the valve face to the ends of the cylinder, amounting in volume to from one to two inches of the stroke, have to be filled with steam at each stroke. To reduce the waste in the passages it is a common practice in large engines to place the valves close up to each end of the cylinder. In a condensing engine, the exhaust pipe *s* leads into the condenser 1, which is fitted with a spray pipe 2, supplied with cold water by the pipe 3, and regulating cock 4. The warm mixture of injected water and condensed steam collects at the bottom of the condenser and is pumped out by the air pump 5, which is actuated by the pump rod 6, which forms a prolongation backwards of the main piston rod *d*. The two suction valves 7. 7, and the two delivery valves 8. 8, are usually made of india-rubber discs beating on metal gratings. The air pump delivers the water into the hotwell 9, and the surplus is run to waste, at a temperature of about 90°, through the overflow pipe 10. The air pump is so named because, although its main duty is to pump water, yet it has also the important office to perform of removing the air which water always contains in variable quantities, and which comes over with the steam from the boiler. A portion of the warm water is conveyed by the pipe 11 to the feed pump 12, which is actuated by the eccentric *t*, and returns to the boiler the quantity of water which is equivalent to the steam used in the cylinder.

The speed of the engine is automatically regulated by the governor 13, which is driven by a belt from a pulley, 14, on the crank shaft of the engine. The governor consists of a pair of balls attached to the ends of levers pivoted to

a central spindle, and prevented from rising, until they attain a certain speed, by a weight acting on the inner and shorter arms of the levers. When the speed of rotation exceeds a certain amount, centrifugal force overcomes the weight, the arms rise up and transmit this movement, by the lever and rod 15, to a regulating value 16, which varies the opening in the main steam-pipe *n*.

In double-acting engines the cylinders, at every complete revolution, have each end filled with steam of the temperature due to its pressure, and the quantity of heat imparted to the metal is so great that a uniformity of temperature is kept up, notwithstanding the variation of pressure in the steam.

When the cylinders are steam-jacketed, the temperature of the working substance is not only maintained, but the pressure is frequently increased, by the evaporation of water, which may be diffused in the steam or have been carried over from the boiler.

According to what law do the steam pressures vary with the variation of volume? If the temperature of liquefaction of steam were further removed from the ordinary temperature which surrounds us, and if the working substance could be prevented from receiving heat while expanding, the pressures would vary according to the ordinates of an adiabatic curve; but, as has been already explained, that cannot take place, because the slightest fall in temperature causes a small portion of steam to revert to the liquid state, and the heat so set free raises the rest of the steam in temperature. In addition, because steam is a good radiator and absorber of heat, the hot sides of the cylinder and piston warm it very quickly, so that, even in an unjacketed cylinder, the pressures vary very nearly as the ordinates of an isothermal curve.

We must, however, invoke the aid of the indicator diagram, to tell us what actually takes place inside the cylinder. Fig. 57 is a representation of three actual diagrams. A

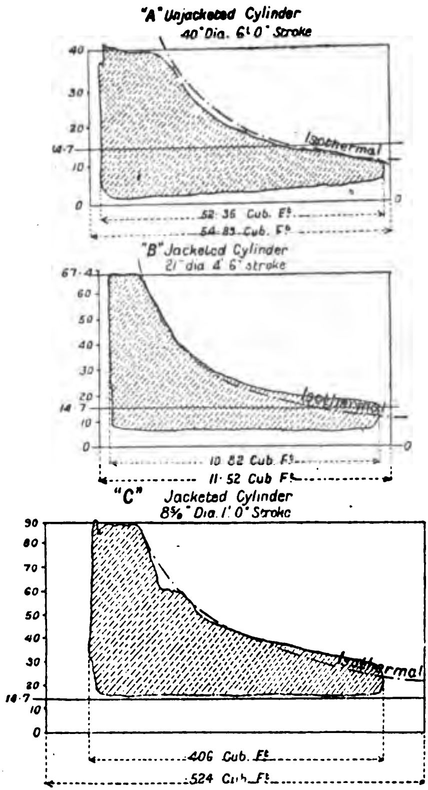


Fig. 57.

was taken from a condensing steam-engine, having an unjacketed cylinder, 40 in. diameter, by 6 ft. stroke. The volume swept through by the piston is represented by the length of the diagram, and amounts to 52·35 c. ft., while

the total volume, which includes the clearance at each end, is represented by the vertical lines beyond the figure at each end, and amounts to 54·89 c. ft. The lowest horizontal line represents absolute zero of pressure, that is, absolute vacuum, and the ordinates,—the absolute pressures per square inch. The horizontal line marked 14·7 represents the standard pressure of the atmosphere. The upper horizontal line represents the initial steam pressure in the cylinder, and the point where the figure suddenly falls away from it indicates the spot where the steam-valve closed, and the steam commenced to expand. At the end of the stroke, the figure drops suddenly again. This marks the point where the valve, communicating with the condenser, opens and allows the imprisoned steam to escape. The lower line of the figure registers the "back pressure," as it is called, that is, the tension of the steam in the condenser, and, finally, the sudden rise of this line indicates the point where steam is again admitted, and the cycle completed. The isothermal curve of expansion has been dotted in; it will be seen how closely it follows the curve traced by the indicator; the temperature of the steam, therefore, has not varied, hence the heat converted into work must have been derived from the heat communicated to the metal of the cylinder and piston during the time that steam was entering. This could only take place by the condensation of a small portion of the steam.

Let us give this action a numerical value.

We have seen that the work done in working expansively along an isothermal curve is given by the formula

$$W = p_1 v_1 \left(1 + \log^e. \frac{v}{v_1}\right) - p_2 v$$

In the particular case we are dealing with, however,

where clearances are to be allowed for, the formula must be amended to the following form.

$$W = p_1 v_1 + p_1 v_2 \log^e. \frac{v_3}{v_2} - p_2 v.$$

p_1 = absolute pressure at beginning of stroke = 40·5 lbs. × 144 sq. in. = 5832 lbs. per square foot.

v = volume swept through by piston = 52·35 c. ft.

v_1 = volume swept through by piston up to the point of cut-off = 13·09 c. ft.

1·27 cubic feet = the volume of clearance and steam passage at each end of the cylinder.

$v_2 = v_1 + 1·27 = 14·36$ c. ft., the total volume of steam expanding.

$v_3 = v + 1·27 = 53·62$ c. ft., the total volume occupied by steam at the end of the stroke.

p_2 = back pressure = 3·8 lbs. × 144 s. in. = 547·2 lbs. per square foot.

$$W = 5832 \text{ lbs.} \times 13·09 \text{ c. ft.} + 5832 \text{ lbs.} \times 14·36 \text{ c. ft.} \times \log^e. \frac{53·62}{14·36} - 547·2 \text{ lbs.} \times 52·35 \text{ c. ft.} = 158{,}076$$

foot-pounds; the diagram actually measures 156,364 foot-pounds, which is a very close agreement.

Since the pressures, in expanding, have varied as the ordinates of an isothermal curve, it follows that the temperature of the steam has not altered, and, consequently, none of its heat has been converted into work; but the heat which has been so converted must have been derived from an extra volume of steam, which was condensed by the relatively cold surfaces it came in contact with, which surfaces again gave it out as the volume of the steam increased, and so compensated for the waste caused by the conversion of some of the heat into

work; in other words, the surfaces of the cylinder acted as carriers of heat from the boiler to the expanding gas. We can easily calculate the quantity of steam condensed.

The work done in each stroke we have seen is 158,076 foot-pounds, corresponding to 204·7 units of heat. The total heat of steam at 40·5 lbs. pressure, and 268° temperature is 1,163 units, and as the condensed steam remains at the same temperature, the available heat is $1{,}163^{u} - (268 - 32) = 927^{u}$; therefore, the weight of steam condensed to supply the heat converted into work will be $\frac{204 \cdot 7^{u}}{927^{u}} = \cdot 221$ lb. Now, the total volume of steam let into the cylinder up to the point of cut-off, was 14·36 cubic feet, the weight of which $= \frac{14 \cdot 36 \text{ c. ft.} \times 62 \cdot 2 \text{ lbs.}}{641 \text{ c. ft.}}$ $= 1 \cdot 393$ lbs., adding to this the weight condensed, we have 1·614 lbs. of steam used per stroke. But of this only ·221 lb. is converted into work, so that the duty is only $\frac{\cdot 221}{1 \cdot 614} = \cdot 137$ or nearly 14 per cent. The mean back pressure was 3·8 lbs., and in the condenser the temperature would at least be that due to the pressure, or 151°, 611° absolute, while the initial temperature is 268°, or 728° absolute, so that our agent is working between these temperatures, and hence, according to Carnot's doctrine, the duty could not exceed $\frac{728° - 611°}{728°} = 16$ per cent., which differs by only 2 per cent. from the duty derived from estimating the comparative weight of steam required for filling the cylinder, and for actual conversion into work. This difference probably arises from the uncertainty as to the temperature of the exhaust steam in the

cylinder. It is sure to be higher than that in the condenser, because the hotter surfaces of the cylinder and piston would warm it up. If t be the true absolute temperature, then $\frac{728° - t°.}{728°} = \cdot 137$

$t° = 628°$; that is, the steam would be 17° hotter than the temperature absolutely necessary to maintain its pressure —which is very likely to be the case.

Fig. 57, B, is an indicator diagram from a condensing-engine with a vertical cylinder 21 in. diameter by 4 ft. 6 in. stroke, the surfaces jacketed all over. The dotted line is the isothermal, the true pressure curve rises above it towards the end of the stroke. The same remark applies to diagram C (Fig. 57), taken from a portable non-condensing engine having a cylinder $5\frac{5}{8}$ in. diameter by one foot stroke, also jacketed all over. Inasmuch as the steam in the jackets is at the same pressure and temperature as that admitted to the cylinders, it follows that the rise of pressure above the isothermal cannot be due to an increase of temperature, but must be caused by the evaporation of water carried over by the steam from the boiler. In these cases the heat converted into work has been derived from the steam in the jackets, transferred by radiation and convection from the metal of the cylinders; the condensed steam withdrawn from the jackets would, therefore, represent the quantity of heat converted into useful work.

When the steam pressure becomes considerable, and a large range of expansion is aimed at, a single cylinder becomes so large, and the strains so severe, that it is more convenient to arrange for the steam to expand in two or more cylinders successively. Engines constructed on this plan are called "compound." The cylinder into which

the steam first enters is the smallest; it exhausts into a large one, and this again into one still larger, and so on.

The action of the steam will be best illustrated by taking a particular case, that of a compound beam engine driving a centrifugal drainage pump at Whittlesea Mere, having a high-pressure cylinder 15 inches diameter by 3'·1½ stroke, and a low-pressure cylinder 25" diameter 4'·6" stroke.

The following are the data required for calculating the power developed through the agency of the steam.

Volume of high-pressure cylinder .	3·835	cubic feet.
Clearance and passages, top end .	·196	„ „
Volume of low-pressure cylinder .	15·338	„ „
Clearance and passages, lower end .	1·124	„ „
Volume of connecting pipe and low-pressure steam chest . .	1·210	„ „
Steam pressure	78·	lbs. absolute.
Mean back pressure in low pressure cylinder	3·15	„ „
Number of revolutions per minute .	32·	

Steam is cut off, in the high-pressure cylinder, at two-thirds of the stroke.

The two piston rods are connected to the same end of the beam, the pistons therefore move together, and the steam from the top of the high-pressure cylinder finishes its work at the opposite end of the low-pressure cylinder.

1. To calculate the total work in the high-pressure cylinder from absolute vacuum, supposing that there is no back pressure. Because the entrance of steam into the cylinder is cut off at ⅔ of the stroke, the volume of steam

admitted would be two-thirds the volume of the small cylinder added to the clearance

$$v = 3 \cdot 835 \times \cdot 667 + \cdot 196 = 2 \cdot 754 \text{ cub. feet.}$$

The pressure at the end of the stroke would be =

$$\frac{78 \text{ lbs.} \times 2 \cdot 754 \text{ c. ft.}}{3 \cdot 835 \text{ c. ft.} + \cdot 196 \text{ c. ft.}} = 53 \cdot 29 \text{ lbs.}$$

The piston moves through $3 \cdot 835 \times \cdot 667 = 2 \cdot 558$ c. ft. under the full pressure from the boiler, and then expansion begins, during which $2 \cdot 754$ c. ft. of steam increase to $4 \cdot 031$ c. ft., therefore the work done

$$W = 2 \cdot 558 \text{ c. ft.} \times 78 \text{ lbs.} \times 144 \text{ sq. in.} + 78 \text{ lbs.} \times 144 \text{ sq. in.}$$
$$\times\ 2 \cdot 754 \text{ c. ft.} \log^{e}. \left(\frac{4 \cdot 031}{2 \cdot 754}\right).$$
$$W = 40{,}517 \text{ foot-pounds.}$$

2. To calculate the total work done in the low-pressure cylinder from absolute vacuum, and supposing that there is no back pressure.

Suppose, in the first instance, that there is no intermediate space between the cylinders, then, at the end of the up stroke, the whole of the steam which had been admitted into the top of the high-pressure cylinder will have been transferred to the bottom of the low-pressure, and will occupy a space composed of the clearance of the high-pressure cylinder, that of the low-pressure, and the whole of the volume of the latter.

$$v_1 = \cdot 196 \text{ c. ft.} + 1 \cdot 124 \text{ c. ft.} + 15 \cdot 338 \text{ c. ft.} = 16 \cdot 658 \text{ c. ft.}$$

and consequently the pressure of the steam will be =

$$\frac{78 \text{ lbs.} \times 2 \cdot 754 \text{ c. ft.}}{16 \cdot 658 \text{ c. ft.}} = 12 \cdot 89 \text{ lbs.}$$

But there is actually 1·21 cub. ft. of passage between the two cylinders, and if we imagine it filled with steam at 12·89 lbs. pressure, the same as that in the low-pressure cylinder at the end of its stroke, it is evident that no alteration will take place in the condition of things at that period, but at intermediate points the existence of this body of steam will affect the pressures. To allow for this we must calculate the volume of 1·21 cub. feet at 12·89 lbs. when raised to 78 lbs. pressure

$$v_2 = \frac{1 \cdot 21 \text{ c. ft.} \times 12 \cdot 89 \text{ lbs.}}{78 \text{ lbs.}} = \cdot 2 \text{ cub. foot.}$$

and we must suppose that so much more steam is admitted into the high-pressure cylinder, that is the volume is increased to 2·954 c. ft.

The volume occupied by the steam the moment communication is established between the cylinders will be :—all the clearances, the intermediate space, and the whole volume of the high-pressure cylinder.

$$v_3 = \cdot 196 + 3 \cdot 835 + 1 \cdot 21 + 1 \cdot 124 = 6 \cdot 365 \text{ c. ft.}$$

and the pressure will fall from 53·29 lbs. at once to =

$$\frac{78 \text{ lbs.} \times 2 \cdot 954 \text{ c. ft.}}{6 \cdot 365 \text{ c. ft.}} = 36 \cdot 2 \text{ lbs.}$$

At $\frac{1}{3}$ of the stroke the volume occupied by the steam will be := all the clearances, the intermediate space, $\frac{2}{3}$ the high-pressure cylinder, and $\frac{1}{3}$ the low-pressure cylinder.

$$v_4 = \cdot 196 + \tfrac{2}{3} \times 3 \cdot 835 + 1 \cdot 21 + 1 \cdot 124 + \tfrac{1}{3} \times 15{,}338 = 10 \cdot 2 \text{ c. ft.}$$

and the pressure $= \dfrac{78 \text{ lbs.} \times 2 \cdot 954 \text{ c. ft.}}{10 \cdot 2 \text{ c. ft.}} = 22 \cdot 59$ lbs. In the same way at $\frac{2}{3}$ the stroke the volume $v_5 = 14 \cdot 033$ c. ft., and the pressure sinks to 16·41 lbs., and at the end of

the stroke the volume consists of the clearances, the intermediate space, and the whole of the low-pressure cylinder.

$$v_6 = \cdot 196 + 1\cdot 21 + 1\cdot 124 + 15{,}338 = 17{,}868 \text{ c. ft.}$$

and the pressure $\dfrac{78 \text{ lbs.} \times 2\cdot 954 \text{ c. ft.}}{17\cdot 868 \text{ c. ft.}} = 12\cdot 89$ lbs. the value which was obtained before.

We thus have $2\cdot 954$ c. ft. of steam at 78 lbs. occupying a volume at the beginning of the up stroke of $6\cdot 365$ c. ft., and $36\cdot 2$ lbs. pressure expanding to $17\cdot 868$ c. ft. As the temperature is not supposed to change, $2\cdot 954$ c. ft. $\times$ 78 lbs. $= 6\cdot 365$ c. ft. $\times$ $36\cdot 2$ lbs., therefore

$$W_2 = 2\cdot 954 \text{ c. ft.} \times 78 \text{ lbs.} \times 144 \text{ sq. in.} \times \log^e. \frac{17\cdot 868}{6\cdot 365} = 34{,}241 \text{ ft.-pounds.}$$

3. The mean back pressure in the low-pressure cylinder, measured from the indicator diagram, was $3\cdot 15$ lbs., therefore the work of overcoming it was

$$W_3 = 15\cdot 338 \text{ c. ft.} \times 3\cdot 15 \text{ lbs.} \times 144 = 6{,}957 \text{ ft.-pounds.}$$

leaving the nett work in the low-pressure cylinder 34,241 ft.-lbs. $-$ $6\cdot 957$ ft.-lbs. $=$ 27,284 ft.-lbs.

4. The back pressure in the high-pressure cylinder during the up stroke was the same as the pressure in the low-pressure cylinder, hence the work done in the low-pressure cylinder is not that represented by the product of the mean pressure into its volume; but the mean pressure multiplied by the difference between the volumes of the low and high-pressure cylinders.

5. The total available work in a single stroke in both cylinders was therefore $= 40{,}517 + 27{,}284 = 67{,}801$ foot-lbs.; the actual power developed measured from the diagram was 58,177 foot-lbs., a discrepancy of 14 per cent.

We next proceed to construct a diagram, Fig. 58, which will illustrate the various stages of the calculations just gone through. The base line A B represents absolute vacuum, and along it the successive volumes assumed by the steam are laid off.

The ordinates represent absolute pressures, A C being equal to 78 lbs. per square inch. A Q represents ·196 c. ft., the clearance of the high-pressure cylinder, while Q J = 3·835 c. ft. is its volume. Steam is cut off when

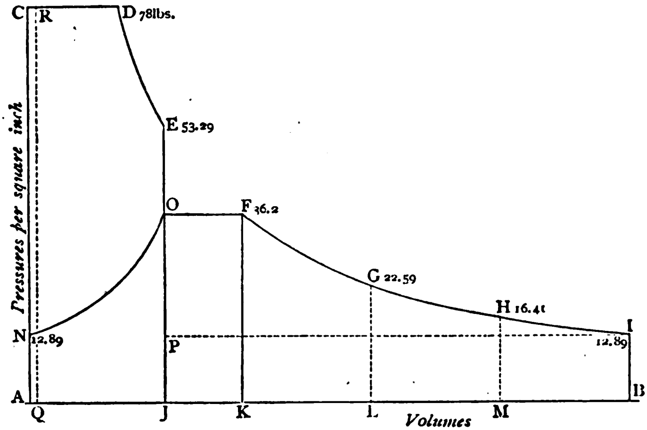


Fig. 58.

the piston has reached the point D, having swept through 2·558 c. ft. D E is the isothermal which defines the pressures assumed by the steam as the high-pressure piston completes its stroke. The pressure at E is 53·29 lbs., but the moment communication is opened between the high-pressure and the low-pressure cylinders, the intermediate space, and clearances of the large cylinder, the volumes of which are represented by J K, receive the steam and the pressure falls suddenly to 36·2 lbs. The

lengths AK, AL, AM, and AB, represent the successive volumes assumed by the steam at the commencement of the up stroke, at $\frac{1}{3}$rd, $\frac{2}{3}$rds, and the complete stroke respectively, and F G H I is the isothermal which defines the corresponding pressures. The terminal presssure I B is 12·89 lbs.; in the actual diagram it is 11·6 lbs. The pressure in the intermediate space J K ranges from J O to J P during the stroke. The isothermals D E and F I do not form parts of the same curve, because the quantity of steam has been augmented in the case of F I, by the amount of steam imprisoned at 12·89 lbs. pressure in the intermediate space. K B does not represent the volume of the low-pressure cylinder, though the figure K F I B represents the nett work done by the steam. The reason of this is that the volumes assumed during the up stroke are composed of decreasing volumes of the high-pressure cylinder added to increasing volumes of the low-pressure cylinder, and not to the changes in one cylinder only, the work in the decreasing small cylinder being negative. The curve N O is the same as the isothermal F I, but with a base equal to the volume of the high-pressure cylinder, and represents the back pressure opposing the motion of its piston in the down stroke on the assumption that the work on the up and down strokes is exactly alike. G L and H M are the pressures at $\frac{1}{3}$rd and $\frac{2}{3}$rds the stroke. In the actual diagram the pressure at F is only $28\frac{1}{2}$ lbs. instead of 36·2 lbs., the theoretical quantity, and at the point O, which is the corresponding spot in the high-pressure cylinder, the pressure should be the same, but it is only 33·4 lbs. The reason of this discrepancy is twofold. Firstly, the difference of nearly 5 lbs. between the back pressure on the small cylinder and the forward pressure on the large is due to the resistance, offered by the

ports and passages, to the rush of steam into the intermediate space,—that is, this pressure represents the head of flow and the head required to overcome friction and the effect of eddies. Secondly, although no external work is done during the transfer of a portion of the steam into the intermediate space, yet considerable energy is expended in acceleration of the steam itself and in friction; a lowering of temperature and partial condensation consequently take place, resulting in a fall of pressure; but this loss is nearly made good by the end of the stroke, where the actual pressure was only ·79 lb. below the theoretical. This result is due to the retardation of the motion of the steam, and to the transfer of heat from the steam jackets. It is evident that it would be advantageous to keep up the temperature of the steam as it passes from one cylinder to the other, so as to avoid some of the loss of pressure; and in many compound engines the steam is passed through heaters of various kinds with very good results; provided, however, that the intermediate space be not, by that means, unduly increased. Many engineers consider that there is an advantage in having a large intermediate vessel between the cylinders, and in cases where the two pistons do not move simultaneously—as, for example, where they are connected to separate cranks placed at angles to each other, as is commonly done in marine engines—an intermediate space is indispensable in order to receive the steam from the high-pressure cylinder while the low pressure-piston is at either end of its stroke, and therefore motionless or moving very slowly. But, theoretically, there is a decided disadvantage in the intermediate space, which is easily shown by calculating the power developed when the intermediate space is increased to 3·835 c. ft., the volume of the high-pressure cylinder; to 9·586 c. ft., the

mean volume between that of the high-pressure and the low-pressure cylinders; and finally to 15·338 c. ft., the volume of the low-pressure cylinder. The results are arranged in the following table:—

Volume of Intermediate space. — Cubic feet.	Work done. — Foot-lbs.	Percentage of work done.
No intermediate space and no clearances,	73,132	100
1·21	67,771	93
3·835	64,916	89
9·586	61,674	84
15·338	60,067	82

The standard case is taken on the supposition that 2·558 c. ft. of steam at 78 lbs. pressure is expanded to 15·338 c. ft., in an imaginary single-cylinder engine in which there are no clearances and no intermediate space. The table serves to show that, theoretically, better results can be obtained out of a single cylinder than out of the compound arrangement. Practical considerations alone render it almost imperative to use high-pressure steam, when highly expanded, in compound cylinders. Thus, for example, if the 78 lbs. pressure be doubled or raised to 156 lbs., then the same work would be done by expending a little less than ·95 c. ft. of steam and allowing it to expand about 16 times, instead of 2·558 c. ft. expanding 6 times; but the pressure on the piston at the beginning of each stroke would be doubled, and therefore the engine would have to be made double the strength to perform the same amount of work. Fig. 59 represents the cylinders of the engine which has been under discussion arranged "tandem"

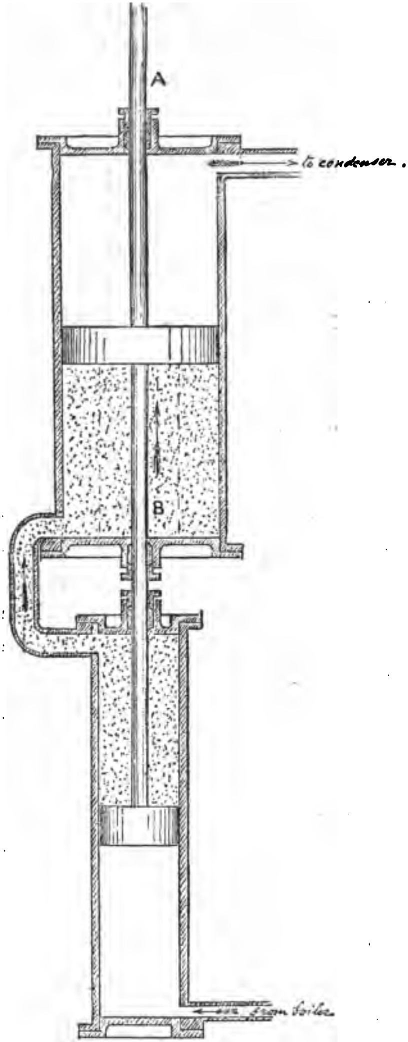


FIG. 59.

fashion, that is to say, one cylinder in line with the other, the pistons being attached to a rod common to both. This arrangement is very common in horizontal engines, and has, of late, found much favour in large vertical marine engines. The pressure transmitted to the piston-rod A, is evidently the whole of the pressure on the high-pressure piston, added to the pressure on the difference of area between the low and the high-pressure pistons, less the back pressure on the low-pressure piston. The contiguous ends of the two cylinders being in communication, the pressure in those ends is the same, hence the high-pressure piston is pushed back as much as the equivalent of its area on the low-

pressure piston is pushed forward, the intermediate piston-rod B being kept in tension by the effort. From Fig. 58 we can get the pressures at every point of the stroke of the two cylinders, hence, making the necessary calculation for a sufficient number of points, we can plot a curve, as in the full line Fig. 60, which will give the pressures on the piston-rod A throughout the stroke. If the work has been correctly done, then the mean pressure measured from the curve multiplied by 4′, 6″, the length of the stroke, will give the total work of 67,771 foot-lbs. calculated by the direct method. To perform the same work, with the same initial pressure of steam in the large cylinder alone, we should have to cut off steam when the piston had swept through 1·69 c. ft.; and this, added to the clearance 1·124 c. ft., would make a total of 2·814 c. ft. at 78 lbs., expanding to 16,462 c. ft. the whole volume of the cylinder with its clearance. The dotted curve, Fig. 60, represents the pressures throughout the stroke. It will be seen at once that the strain at the beginning of the stroke on the piston-rod in the compound engine is only 21,346 lbs. against 36,742 lbs. in the case of the single cylinder, while, on the other hand at the end of the stroke, the compound arrangement gives 9,736 lbs. against 5,478 lbs. in the single cylinder. This uniformity of pressure may, however, not be always advantageous especially in quick-running engines, for the reasons explained in Chapter I.

The engine we have been discussing makes 32 revolutions per minute, hence each stroke is performed in $\frac{60}{64} =$ ·93 of a second, and during that brief space sufficient heat is imparted, by radiation and conduction, to the expanding steam to replace the heat converted into work. This rapidity of action is due to the adiathermanous nature of

steam and water, in consequence of which radiant energy, especially, is very quickly transferred to the molecules of the gas.

The quantity of steam at 78 lbs. pressure admitted to the high-pressure cylinder and which acted as agent only, was 2·754 cub. feet, weighing ·5019 lb. The theoretical

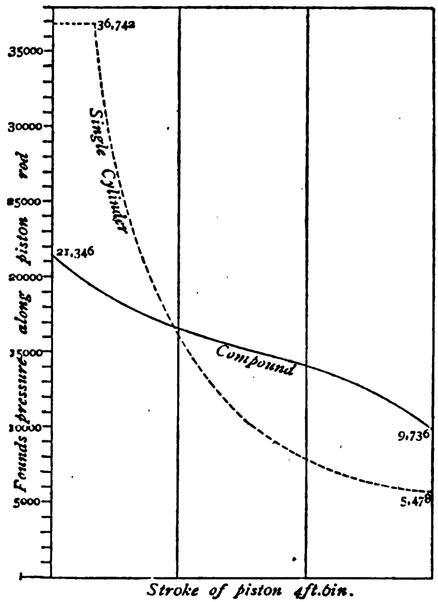


FIG. 60.

amount of work which might have been performed was 67,771 foot-pounds, corresponding to 87·79 units of heat. The heat converted into work was derived from steam condensed at very little below the temperature due to its initial pressure, or 310·2°. The total heat from 32° per pound of steam was

$=1091 \cdot 7^\circ + \cdot 305\ (310 \cdot 2^\circ - 32^\circ) = 1176 \cdot 6$ units, and the number of units per pound condensed $= 1176 \cdot 6^u - (310 \cdot 2 - 32) = 898 \cdot 4^u$; therefore the weight of steam converted into work was $= \frac{87 \cdot 79^u}{898 \cdot 4^u} = 0 \cdot 0977$ lb.

Thus we have

Steam acting as agent only . .	0·5019 lb.
Steam converted into work . .	0·0977 „
Total used per stroke . . .	0·5996 „

The proportion which the steam, the heat of which had been converted into work, bears to the total steam used was $\frac{0 \cdot 0977}{0 \cdot 5996} = \cdot 163$, or nearly 16½ per cent.

Supposing that the stroke were performed in one minute, 67,771 foot-pounds would yield 2·054 horse-power, and the consumption of steam per hour would have been $\frac{\cdot 5996 \text{ lb.} \times 60 \text{ minutes}}{2 \cdot 054 \text{ h.-p.}} = 17 \cdot 51$ lbs., which would be extremely good duty. The actual power realised, as measured from the indicator diagram, was 58,177 foot-lbs. or 1·76 horse-power; the consumption of steam was therefore 20·4 lbs. per indicated horse-power, which is not far from the actual performance of this engine.

Because the number of units of heat in steam above 32° increases in direct proportion to the increase of its temperature, the law of Carnot will apply; and we should expect to find the ratio of the fall of temperature to the initial absolute temperature to be about the same as the proportion of steam converted into work to the total steam used, that is to say, about 16½ per cent. The absolute temperature of 78 lbs steam is 770·2.° The temperature due to the 3·15 lbs back pressure in the condenser is 603·3°;

hence the duty should be $\frac{770 \cdot 2 - 603 \cdot 3}{770 \cdot 2} = \cdot 216$ about 30 per cent higher than the first estimate. This discrepancy, as already stated, arises from uncertainty as to the temperature of the steam flowing into the condenser. At the end of the stroke, just before exhausting, the temperature must have been very little less than $770 \cdot 2^\circ$; the steam does no external work in flowing into the condenser, hence it is probable that the temperature will be maintained higher than that due to the pressure for the greater part of the stroke.

The temperature of the steam, acting as agent, is kept up, in this case by the heat conveyed by conduction and radiation from the steam jackets, and consequently the steam condensed in the jackets ought to represent the work done.

A practical illustration of this fact may be seen in the case of a pair of pumping-engines at the Lambeth Waterworks, Brixton.

These engines were found to consume $16 \cdot 8$ lbs. of steam per horse-power per hour in the cylinders, and $2 \cdot 8$ lbs. in the jackets. Steam was at $54 \cdot 4$ lbs. pressure above the atmosphere, or $69 \cdot 1$ lbs. absolute and 302° temperature.

The total heat of 1 lb. of steam under these conditions is $1{,}174^u$ from the freezing-point; hence, as the steam was condensed to water at very little below its own temperature, the heat parted with was 904^u per 1 lb., corresponding to work per minute

$$\frac{2 \cdot 8 \text{ lbs.} \times 904 \text{ lbs.} \times 772^J}{60 \text{ min.}} = 32{,}569 \text{ foot-lbs.,}$$ which is a little less than a horse-power.

The duty done by $19 \cdot 6$ lbs. of steam per horse-power per hour was therefore represented by the ratio which $2 \cdot 8$

lbs. condensed bore to the total weight used $= \frac{2 \cdot 8}{19 \cdot 6} = \cdot 142$. The range of temperature could not have been more than 149°, that is, from 302°, the initial temperature of the steam, to that of the condenser corresponding to 4 lbs. average back pressure, say, 153°; hence the limit of duty would be, according to Carnot, $= \frac{149°}{762°} = \cdot 195$, about 37 per cent. more than in the previous estimate, the discrepancy being due, as has already been pointed out, to the uncertainty as to the temperature of the steam in the cylinder on the vacuum side.

In the investigations just completed, one source of error has been neglected, namely, the effect of the steam left in the clearances and passages of the low-pressure cylinder. These spaces amount to 1·124 cub. ft., and, by the time the exhaust is completed, the pressure has fallen to 2·2 lbs.; the equivalent amount of steam, therefore, at 78 lbs. is only $= \frac{1 \cdot 124 \times 2 \cdot 2}{78} = \cdot 032$ cub. ft., which should be added to the quantity of steam expanding in the low-pressure stroke.

Besides the negative work done by back pressure, the energy expended in pumping out the injection water and forcing the feed water into the boiler should be deducted from the work done in the cylinders.

The total weight of steam used per stroke is ·5996 lb. at 78 lbs. pressure, containing 1176·65 units of heat per 1 lb. of steam, measured from 32°. The water used in condensing generally flows away at 100° or 68° above the freezing point, so that the number of heat units to be disposed of per 1 lb. of steam is $1176 \cdot 65^{u} - 68^{u} = 1118 \cdot 65^{u}$, and per stroke $= 1118 \cdot 65 \times \cdot 5996 = 670 \cdot 7^{u}$;

of this quantity 87·8 units has been converted into external work, hence 582·9ᵘ remain to be carried off by the condensing water. Supposing the injection to be at 60°, its rise in temperature will be 40°, corresponding to the same number of heat units per pound of water, so that the weight of water required to condense the steam will be $\frac{582 \cdot 9^u}{40^u} = 14 \cdot 57$ lbs. or 1·457 gallons, and the weight to be pumped will be this amount added to the weight of steam used, making altogether 15·17 lbs. equal to ·24 cubic ft. per stroke.

The work of pumping consists of lifting the water about 2 ft. 3 inches, which is the stroke of the air-pump, and forcing it out against a pressure equal to that of the atmosphere, less the back pressure in the condenser at the end of the low-pressure stroke, which, from the indicator diagram, is found to be 2·2 lbs. Therefore

$$\text{Work} = 15 \cdot 17 \text{ lbs.} \times 2 \cdot 25 \text{ ft.} + \cdot 24 \text{ c. ft.} \times (14 \cdot 7 \text{ lbs.} - 2 \cdot 2 \text{ lbs.}) \times 144 = 466 \text{ foot-lbs.}$$

The total work in the cylinders was 67,771 foot-lbs., so that the negative work in the air-pump is only $\frac{466}{67{,}771} = \cdot 007$, or a little less than three-quarters per cent. The quantity of water used per horse-power is $\frac{1 \cdot 457 \text{ gallons}}{2 \cdot 054 \text{ h.-p.}} = \cdot 709$ gallon per minute, or on the actual horse-power, which we found to be 1·76 h.-p. per stroke, the quantity is ·83 gallon per minute. The usual allowance is one gallon per indicated horse-power per minute.

In tropical climates, where the water is often between 80° and 90°, a proportionately larger amount of injection water is required. The condensation of the steam

represents the destruction of the agent, by transferring its heat energy to a large body of water which must be allowed to flow unproductively away.

The advantage obtained by condensing the steam is very great. If the engines were non-condensing, there would probably be a back pressure of about half a pound above the atmospheric pressure, or 15·2 lbs. absolute; the mean back pressure in the condenser was taken at 3·15 lbs., hence the loss of work would be

$= 15 \cdot 33$ c. ft. $(15 \cdot 2 - 3 \cdot 15)$ lbs. $\times$ 144 sq. in. $= 26{,}615$ foot-lbs.; this has been saved at the cost of 466 foot-lbs. expended in working the air-pump.

The volume of air pumped out at every stroke is very minute, a few bubbles only may be observed escaping from the water as it is forced out through the delivery valves of the pump; yet, if not regularly removed, air would accumulate in the condenser and gradually destroy the vacuum.

The weight of feed water pumped in at each stroke is equal to the total weight of steam used, or ·5996 lb., corresponding to ·00964 cubic ft. The work done in forcing this into the boiler $= 00964$ cub. ft. $\times$ (78 lbs.—14·7 lbs.) $\times$ 144 sq. in. $= 87 \cdot 87$ foot-pounds, which constitute only a little more than one-tenth per cent. of the work done by the same water in the form of steam. The feed water is generally taken from the hot well of the air-pump, so that $\cdot 5996$ lb. $\times (100^\circ - 60) = 24$ units of heat per stroke are saved from out the hot injection water running to waste.

When circumstances permit of the cylinders being placed at a higher level than the boilers, it is a common practice to connect the steam-jackets with the boilers, so that the condensed steam shall drain continually back into

them; and in some cases the cylinder is placed actually in the boiler, so that the steam surrounds it completely, and in that manner makes a most perfect steam-jacket.

From the foregoing investigations it will be seen that steam does not differ from air in a hot-air engine, or from the mixture of gases in a gas engine, in being merely the agent of transforming a certain amount of heat imparted to it into useful work. The circumstance that the agent has to be manufactured from its liquid state, at great cost, is a disadvantage, because we cannot utilise much of the heat so expended; and is also the cause why, in steam-engines, the useful effect obtained necessarily bears so small a proportion to the total energy imparted to the agent in its liquid form.

It is difficult to realise the proposition that the gases used as agents in heat-engines are not the actual sources of power. The truth is, that their function is similar to that of a train of wheelwork, or of a lever, in transmitting a mechanical effort. A common lever, used for the purpose of raising a weight, is an agent by means of which a force is caused to perform certain work, but the lever itself has no influence at all on the result. Provided the length of the arms be kept at a constant ratio, the action will not be affected by the lever being short or long, light or heavy, of wood or of iron. There is, however, this difference between the lever and the gaseous agent, namely, that the former can be used over and over again, without in any manner deteriorating or changing its nature, consequently its first cost is not of much moment in comparison with the work it is capable of transmitting; but the gaseous agents have to be produced and thrown away in each cycle, hence their first cost, that is the cost of generating steam or heating air, is of great consequence, and it is

upon the economy with which the agents are produced and used that the efficiency of heat-engines depends. Now the weight of the agent used, in proportion to the power developed, decreases with the increase of the range of temperature through which it works, and with the increase of the rate of expansion, hence the efficiency of steam-engines depends on the initial pressure, and therefore, temperature of the steam, and upon the number of times it is caused to expand. This is illustrated graphically in diagram (Fig. 61), which shows, by means of curves, the volume

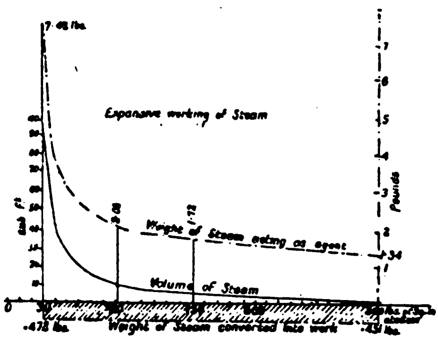


FIG. 61.

and weight of steam required to yield 378,720 foot-pounds of work in a cylinder of 100 cubic feet capacity, with a back pressure of 3·7 lbs., and steam pressures ranging from 30 lbs. to 300 lbs. absolute. At 30 lbs. pressure, without any expansion, the required work is produced at an expense of 7·42 lbs. of steam. At 100 lbs. pressure, $8\frac{1}{2}$ cubic feet, weighing 1·96 lbs., expanding along the isothermal, will produce the same result; and at 300 lbs. 2·07 cubic feet, weighing 1·34 lbs. It will be observed how rapidly an economy is effected up to about 100 lbs. pressure, cutting off at $8\frac{1}{2}$ per cent.; after that the economy

increases much more gradually, so that a point will soon be reached, in practice, where the mechanical difficulties connected with the use of steam at high pressures and temperatures will no longer be balanced by a saving of fuel.

The dotted line under the base shows the weight of steam, the heat in which is actually necessary for conversion into work; this quantity is nearly constant, being a little greater at the lower pressures. Between 90 lbs. pressure and 150 lbs. there is, according to the diagram, a reduction of steam used from 2·05 lbs. to 1·72 lbs., a saving of 16 per cent. Mr. List, chief engineer to the Donald Currie Line, has furnished some valuable information respecting the effect which an increase of pressure with corresponding increase of temperature and rate of expansion, obtained by the introduction of treble expansion engines, has had on the economy of fuel. An ordinary double cylinder compound engine, working with 90 lbs. pressure, consumed 1·59 lbs. of coal per horse-power per hour; the treble cylinder compound, under 150 lbs. pressure, consumed only 1·3 lbs., a gain of 18 per cent., which agrees pretty well with the theoretical estimate.

The pressure of steam acting on a piston, if the latter be free, as in a Cornish pumping engine, produces accelerated motion of irregular velocity depending upon the rate of expansion, and this has to be very carefully adjusted so that the retarding forces, consisting of the work done by the engine and its friction, shall bring the moving parts to rest at the end of the stroke. In rotative engines, the speed of the piston and its exact range, are controlled by the crank; but still it is necessary, in order to ensure smooth working, that there shall be a certain relation between the accelerating force acting on the piston, the weight of the moving parts, and their velocity, especially

in engines running at a high speed; and it is possible so to adjust them, that the work done in the second part of the stroke, when the reciprocating parts are coming to rest, shall just balance the energy communicated in the first part. If matters are not so adjusted, severe pressures are produced at the turn of the stroke on the various portions of mechanism. The principles involved were fully investigated in Chapter I.

There is an ingenious arrangement of balanced engine in which two cylinders are set opposite to each other, with their pistons connected to cranks also opposed one to the other, so that the reciprocating parts are always either moving towards or receding from each other. In consequence of this disposition, when the weights moved by the two cylinders are alike, the strains due both to steam-pressure and momentum balance each other in all positions, and the crank shaft has only the torsional strains to carry; the consequence is that the engine may be run at a very high velocity, and can be advantageously used for driving high-speed machinery direct.

Parsons's Engine.

One of the earliest and most obvious forms of steam engine was an arrangement by which a jet of steam impinged upon the sails of a small windmill; but this apparatus remained a mere toy until the early part of 1884, when the Honourable C. A. Parsons introduced a motor in which the rude idea above alluded to was, by the aid of high scientific knowledge and great mechanical ability, developed into a machine which will probably prove to be the best and most economical of high-speed motors.

When a jet of steam is allowed to issue from a steam boiler, the molecules composing the gas are endowed with a very high velocity, the approximate value of which may be arrived at in the following manner. Steam issuing either into the atmosphere or into a vessel under some lower pressure, performs external work consisting in the acceleration of its own molecules, and in overcoming the resistance of the pressure against which the jet issues. If steam were a permanent gas at ordinary temperatures, then the energy latent in the issuing jet would be equal to the work done in expanding along an adiabatic curve; therefore, if u be the velocity of the jet, p_1 v_1 the initial absolute pressure and corresponding volume of the steam, p the back pressure, then the energy per pound of steam =

$$\frac{u^2}{2g} = \frac{p_1 v_1 \gamma}{\gamma - 1}\left\{1 - \left(\frac{p}{p_1}\right)^{\frac{y-1}{y}}\right\}$$

$$\text{whence } u = \sqrt{\frac{2 g p_1 v_1}{\gamma - 1}\left\{1 - \left(\frac{p}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\}}$$

The value of γ for steam is $1 \cdot 3$, therefore assuming p_1 = 78 lbs. absolute v_1 will be $5 \cdot 506$ c. ft. p = $14 \cdot 7$ lbs.

$$u = \sqrt{\frac{64 \cdot 4 \times 78 \text{ lbs.} \times 144 \text{ s. in.} \times 5 \cdot 506 \text{ c. ft.} \times 1 \cdot 3}{\cdot 3}\left\{1 - \left(\frac{14 \cdot 7 \text{ lbs.}}{78 \text{ lbs.}}\right)^{\cdot 23}\right\}} = 2346 \text{ ft.}$$

But the temperature of the steam, which was $770 \cdot 2°$ absolute, should fall, in expanding and doing work, to

$$\frac{770 \cdot 2°}{\left(\frac{78 \text{ lbs.}}{14 \cdot 7 \text{ lbs.}}\right)^{\cdot 23}} = 524 \cdot 3°$$ or to only 64° on the Fahrenheit scale, at which temperature it is incapable of existing at atmospheric pressure. The temperature will be 212°, and

consequently the heat converted into work will have been derived in part, as has already been pointed out, by the condensation of a small portion of the steam; hence the terminal temperature being higher, the pressure would also be higher and the velocity of the jet greater. If we suppose the temperature of the jet unchanged, the expansion would take place along the isothermal and

$$\frac{u^2}{2g} = p_1 \, v_1 \log^e. \left(\frac{p}{p_1}\right)$$

$$u = \sqrt{2 \, g \, p_1 \, v_1 \log^e. \frac{p_1}{p}}$$

and in the particular case under consideration

$$u = \sqrt{64 \cdot 4 \times 78 \text{ lbs.} \times 144 \text{ s. in.} \times 5 \cdot 506 \times \log^e. \left(\frac{78 \text{ lbs.}}{14 \cdot 7 \text{ lbs.}}\right)} = 2578 \text{ ft.}$$

The actual velocity will be between these two, and may be taken at the mean or 2462 feet per second; and the kinetic energy of 1 lb. will be $\frac{2462^2}{64 \cdot 4} = 94{,}122$ foot-pounds, or, if the pound of steam were discharged in one minute, it would be capable of yielding $\frac{94{,}122 \text{ ft.-lbs.}}{33{,}000} = 2 \cdot 852$ horse-power at an expenditure of 60 lbs. of steam per hour, and therefore the consumption of steam per horse-power per hour would be $= \frac{60 \text{ lbs.}}{2 \cdot 852 \text{ h.-p.}} = 21$ lbs. which would be a duty beyond the reach of the best non-condensing reciprocating engine. It is evident, therefore, that if the energy of the jet could be taken up by any mechanical contrivance, an economical engine would very possibly result. With this object Mr. Parsons has contrived a machine (Fig. 62), based on the "parallel flow," or

"Jonval" turbine hydraulic motor; that is to say, he causes the steam to flow through a fixed ring of directing blades on to a revolving ring of similar blades, the flow of the steam being, generally, parallel to the axis about which the revolving blades turn. But in order to secure efficiency in this class of motors, it is necessary that the outer periphery of the revolving blades should move nearly as fast as the jet of steam; so that if the wheel were 4 inches in diameter or a little over one foot in circumference, and if the steam pressure were 78 lbs. per square inch absolute, then the wheel would have to revolve about 2000 times a second, which would be utterly impracticable. To overcome this difficulty, the steam is made to work, in succession, through a number of wheels passing from the first into the fixed guide-blades of a second, and from the second to the fixed guide-blades of a third; and so on through some twenty wheels all secured to the same shaft. Now, in utilizing a high fall of water there is no loss, theoretically, if the fall be divided into several steps; as, for example, by a series of water-wheels by means of which the same water is used in succession. In the case of steam the same law holds good, because the velocity of flow being proportional to the square root of the pressure, the energy due to the velocity is directly proportional to the pressure, so that if the fall of 78 lbs.—14·7 = 63·3 lbs. pressure be divided equally between 20 wheels, the steam would pass from one wheel to another under a pressure of only 3·165 lbs. per square inch. But the velocity with which steam flows under a constant pressure increases with the diminution of its absolute pressure on account of the increase of volume and consequent diminution of specific weight; thus the velocity in the first wheel due to a fall of pressure from 78 lbs. to 74·835 lbs.

will be 405 feet per second calculated as expanding along the adiabatic, while in the last wheel the volume is reduced in consequence of the fall of temperature and the condensation of a portion of the steam to provide the heat converted into external work, but increased by reason of the fall of pressure. The units of heat converted into work will be $\frac{94{,}122 \text{ foot-lbs.}}{772}$ = 121·9ᵘ. These will be derived from the cooling of 1 lb. of steam from 310·2° to 212° = 29·9ᵘ, and from the condensation of ·096 lb. of steam yielding ·096 lb. × 966 lbs. = 92ᵘ. But ·096 lb. of steam at 212° represent 26·36 c. ft. × ·096 lb. = 2·53 c. ft., hence the volume passing out of the last wheel will be 26·36 c. ft. – 2·53 c. ft = 23·83 c. ft. per 1 lb. of steam used and

$$u = \sqrt{\frac{64 \cdot 4 \times 14 \cdot 7 \text{ lbs.} \times 23 \cdot 83 \text{ c. ft.} \times 144 \text{ s. in.} \times 1 \cdot 3}{\cdot 3}\left\{1 - \left(\frac{14 \cdot 7}{17 \cdot 865}\right)^{\cdot 23}\right\}} = 787 \text{ feet.}$$

The mean velocity would be about 596 feet per second, which would correspond to 35,760 revolutions per minute of a 4-inch wheel, supposing its periphery to run the same speed as the steam. In practice about 12,000 revolutions per minute have been attained.

The Parsons motor differs from most other steam engines in this respect, that the steam travels continuously from end to end, there is no alternate heating and cooling of the opposite ends as in all reciprocating engines; hence the temperature of the apparatus, at any point, will be constant, and the heat which is converted into external work, if the engine be not steam jacketed, must be taken from the steam flowing through.

When steam issues, as a jet, from a boiler its temperature

falls at once to about 212°, the temperature corresponding to the atmospheric pressure; hence the volume of steam issuing from the motor will be reduced by fall of temperature in the proportion of $\frac{672^\circ}{770^\circ}$ or about 87 per cent., and by the volume of steam the heat of which, as we have seen, has been converted into work, so that the volume issuing per 1 lb. will be 23·83 cubic feet against 5·506 cubic feet, the volume of the same weight at 78 lbs. pressure. The velocity of the steam will be increased, however, from 405 feet to 787 feet per second, so that the steam aperture through the last wheel should be increased above that in the first in the proportion of $\frac{23 \cdot 83 \text{ c. ft.}}{5 \cdot 506 \text{ c. ft.}} \times \frac{405 \text{ ft.}}{787 \text{ ft.}} = 2 \cdot 23$ times, supposing it to be desirable that a constant difference of pressure were maintained from wheel to wheel. The motor is actually constructed in this manner, each successive wheel has slightly deeper blades, and possibly set at different angles, so as to increase the area of opening, probably even beyond the ratio indicated, in order to reduce the velocity of flow towards the end of the series. In order to balance the end pressure on the wheels they are arranged as two sets on either side of the steam entrance. The steam flows right and left, and the opposing pressures are counteracted by the connecting shaft which is common to both. The turbine motor is eminently fitted for driving high-speed machines such as fans, centrifugal pumps, and dynamos; the motion is absolutely continuous without any variation of effort during each revolution, and the speed to be attained is almost without limit; hence all countershafts, belts, and speed-multiplying arrangements are dispensed with. Mr. Parsons states that, in practice, his motors compare favour-

ably in economy, with respect to the expenditure of steam, with compound engines encumbered with the countershafts and belts necessary to attain the high speed required by dynamos. The investigations we have just completed render it extremely probable that Mr. Parsons's estimate is in no way exaggerated.

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